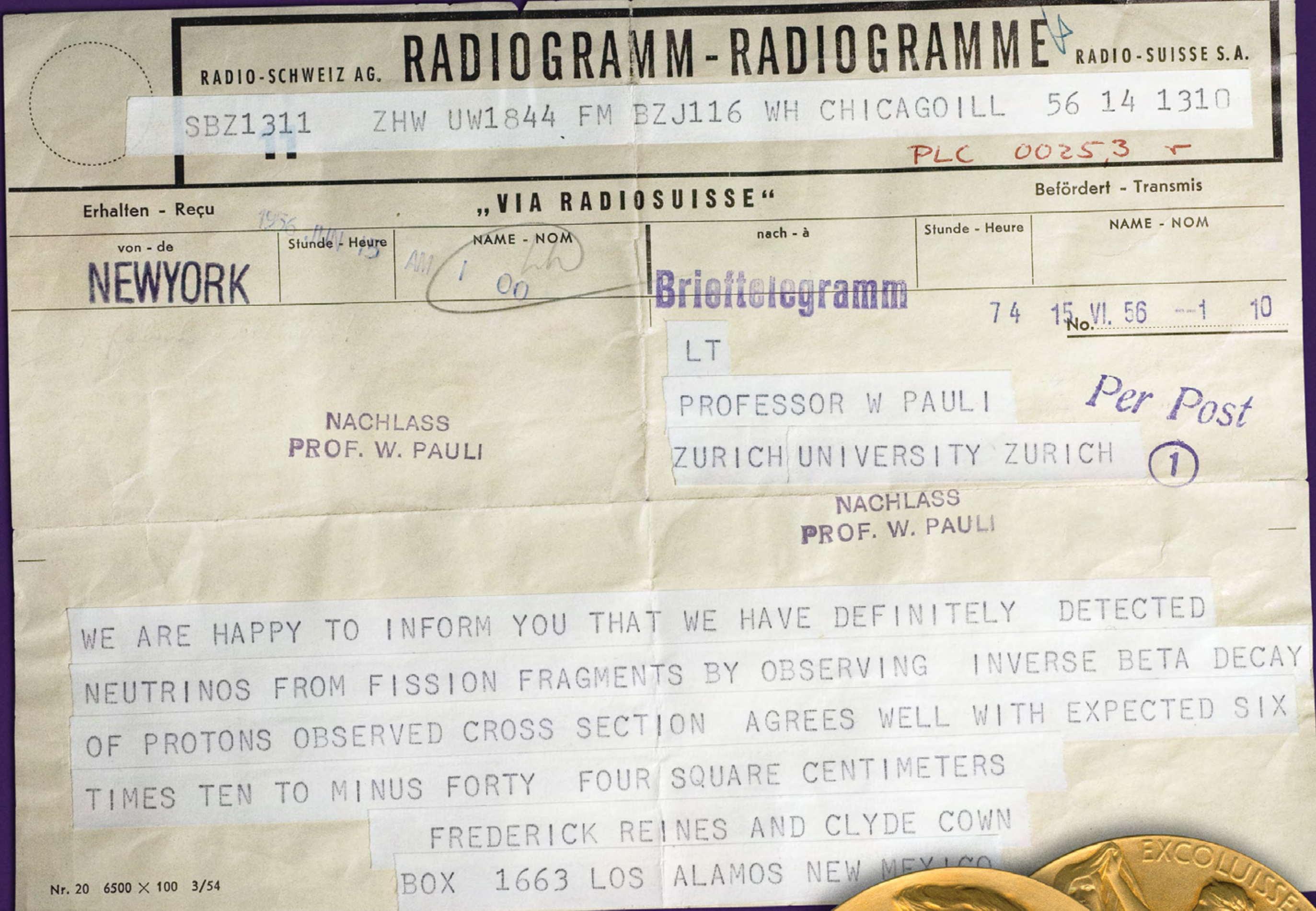
LOS ALAMOS NATIONAL LABORATORY

1663

75 YEARS

OF SCIENCE AND TECHNOLOGY ON THE HILL



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PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO

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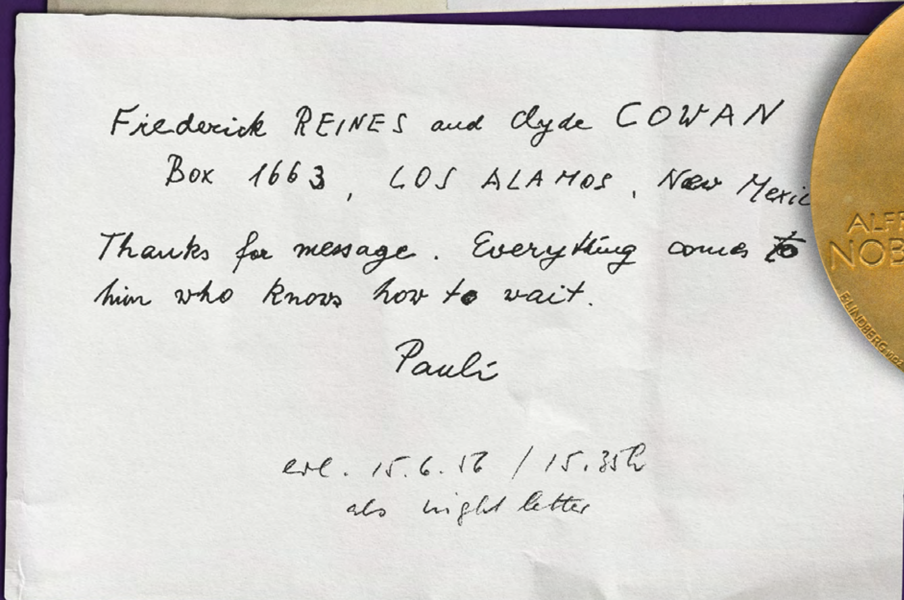

Frederick REINES and Clyde COWAN

Box 1663, LOS ALAMOS, New Mexic

Thanks for message. Everything comes to him who knows how to wait.

Pauli

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als Night letter

When Los Alamos scientists Fred Reines and Clyde Cowan finally proved the existence of neutrinos in 1956, they sent a telegram to inform Wolfgang Pauli, who had first proposed the elusive particles 26 years earlier. Pauli's reply was short and profound. Reines was awarded the 1995 Nobel Prize in physics for detecting the neutrino (Cowan died in 1976). For more about neutrino science at Los Alamos, see "Bringing Neutrinos Back to Los Alamos," on page 10.

CREDITS: Communiqués, European Organization for Nuclear Research (CERN); Nobel medallion, Bradbury Science Museum/LANL

1663

LOS ALAMOS SCIENCE AND TECHNOLOGY MAGAZINE

ABOUT THE COVER

Often when *1663* asks scientists how they came to join Los Alamos, they recount the vivid experience of driving up "the Hill" for the first time, ascending the dramatic ledge-style road set within pastel-orange canyon walls and emerging at the town and sprawling Laboratory atop the Pajarito Plateau, at the base of the beautiful Jemez mountains. The road has been rerouted a bit over the years, but the experience was essentially the same for the scientists, military personnel, and others joining the Manhattan Project when the Laboratory was first established 75 years ago in 1943. Happy anniversary, Los Alamos—and may you continue to advance the nation's science and security for many more.

ABOUT OUR NAME

During World War II, all that the outside world knew of Los Alamos and its top-secret laboratory was the mailing address—P. O. Box 1663, Santa Fe, New Mexico. That box number, still part of our address, symbolizes our historic role in the nation's service.

ABOUT THE LDRD LOGO

Laboratory Directed Research and Development (LDRD) is a competitive internal program by which Los Alamos National Laboratory is authorized by Congress to invest in research and development that is both highly innovative and vital to national interests. Whenever *1663* reports on research that received support from LDRD, this logo appears at the end of the article.

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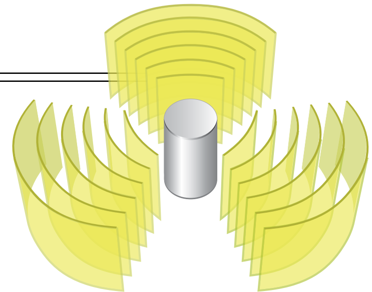
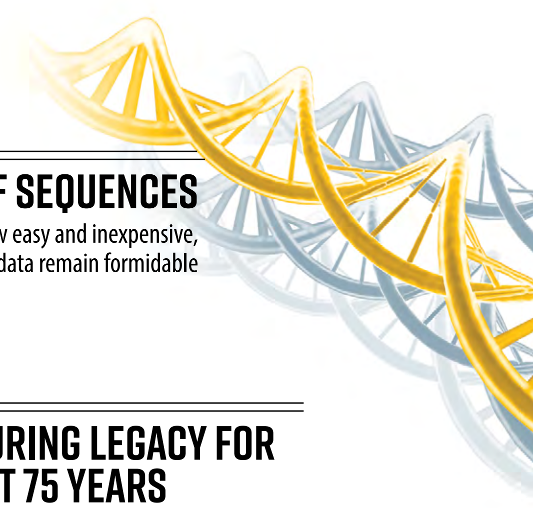
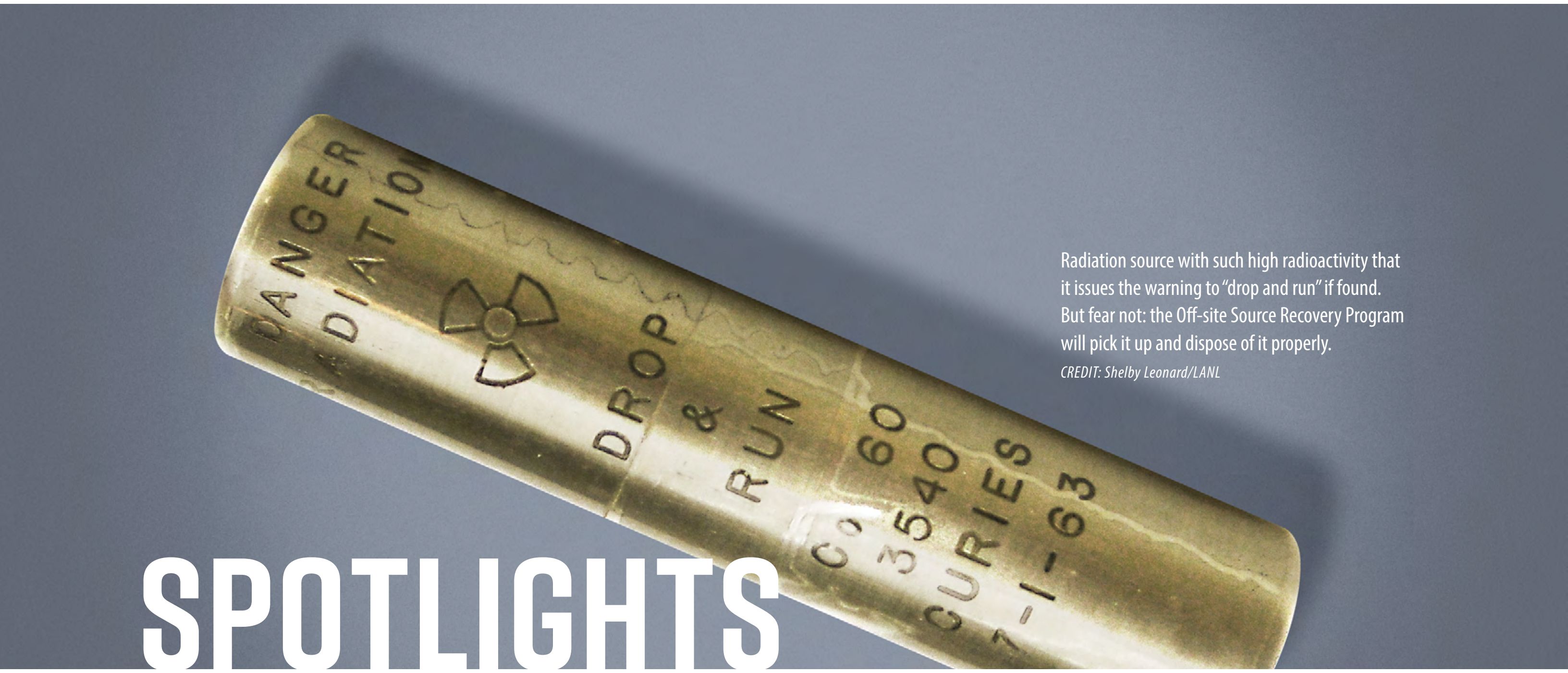


CREDIT: © 2006 David Monniaux





Radiation source with such high radioactivity that it issues the warning to "drop and run" if found. But fear not: the Off-site Source Recovery Program will pick it up and dispose of it properly.
CREDIT: Shelby Leonard/LANL

SPOTLIGHTS

Careful with Hot Objects

The world has been producing sealed radioactive sources for more than a century. Some are found in government research laboratories. Some are found in medical centers. Some are found in university science classrooms. Some are found in industrial or agricultural settings. Many are no longer needed or no longer suitable for their original purpose—and may have dropped off the radar of those tasked with managing them. But they're still out there, posing a potential health risk to the public. And if they fell into the wrong hands, they could be incorporated into a radiological dispersion device, also known as a dirty bomb.

"In the 1990s, several Los Alamos scientists had the foresight to recognize that something had to be done," says Becky Coel-Roback, Los Alamos program manager for the Off-site Source Recovery Program (OSRP), a coordinated effort between the Los Alamos and Idaho national laboratories to round up sealed radioactive sources that are no longer in use. "And we're proud to still be doing it, successfully, 20 years later."

Indeed, having been formally established in 1998 after a successful pilot program the year before, OSRP marks its 20th anniversary this fall. During that time, it has collected more than 41,000 radioactive sources from more than 1400 sites, spanning all 50 states and 26 foreign countries. The collective radioactivity of all those removed sources exceeds 1.25 million curies, enough to produce thousands of dirty bombs.

Initially, OSRP recovered only transuranic sources (beyond uranium on the periodic table), since such material did not have a commercial disposal pathway. These sources contained isotopes such as plutonium-238 (used as power sources, such as in pacemakers), plutonium-239 (used in reactors), and americium-241 (used in industrial gauges). In 2003, the mandate expanded to include many other isotopes of concern, such as strontium-90, cobalt-60, cesium-137, and radium-226, which are the most common isotopes used in high-activity medical, research, and industrial applications. Unfortunately, although such radioactive sources are fairly common, not all have a viable disposal pathway at the end of their useful lifetime, making OSRP removal and disposition critically important.

In addition to recovering and securing radioactive material directly, the OSRP team conducts training, assessment, and consulting—covering broad source-management strategies as well as specifics, such as packaging, transportation, and secure storage. It does this both at home and abroad. It also supports reducing global reliance on radioactive sources by recovering devices replaced by non-radiological alternative technologies. And recently, it has successfully overseen the development, testing, and certification of a specially designed "Type B" shipping container for compliant transportation of high-activity sources; the container was put into official use earlier this year. In 20 years of safeguarding "hot" objects, this is just the latest in a long line of milestones—part of the something that had to be done.

—Craig Tyler

Qubit Queries

A true, universal, and fault-tolerant quantum computer exists only in concept. If built, it could create, maintain, and manipulate information in quantum bits, or qubits, to perform calculations that normal computers have so far been unable to do efficiently. Because in this context "do efficiently" could mean "do within our lifetime," a true quantum computer would represent, quite literally, a quantum leap in computing.

The concept goes roughly like this: You prepare subatomic particles representing qubits in a particular state (say, all in the ground state, representing all zeros). You perform some operation on them (say, fire a series of laser pulses), causing them to interact in a prescribed way, and then measure some property that corresponds, with a high probability, to the correct answer to a computational problem. It's a tall order because of the difficulty in isolating the submicroscopic particles from all external influences, while at the same time being able to manipulate them and extract information from them.

Partial quantum computers already exist—machines that offer a particular mechanism for working with qubits, allowing them to do a subset of the tasks a true quantum computer could do—and Los Alamos is one of the few institutions that has one [see "Not Magic, Quantum," in the July 2016 issue of *1663*]. For both the partial quantum computer already on site and the true quantum computer of the future, Los Alamos's Rolando Somma is working to develop the algorithms needed to unleash the full potential.

"We can't categorically state that classical computers are incapable of doing what quantum computers can do," says Somma. "Someone could always discover a new way to do things classically. But these efforts have all failed so far, and in many cases, we have found a more natural quantum algorithm that does the trick."

A classical computer bit is a two-level structure, 0 or 1. It can be manipulated via a logical operation called a gate, such as the NOT gate (which converts 0s into 1s and 1s into 0s) or the AND gate (which combines two bits such that two 1s combine to return 1 and other combinations return 0). Deep down, computer routines, such as if-then instructions or arithmetic computations, are built from logical gates like these.

A qubit is also built from a two-level structure, but in addition to 0 and 1, it can exist in a superposition, or mixture, of both 0 and 1. So in addition to classical logical gates, a qubit can also support additional, purely quantum gates, such as the Hadamard gate (which converts a 0 or 1 into an equal superposition of 0 and 1) or the phase gate (which attaches a phase to a 0 or 1, affecting probabilistic quantum behavior). In principle, any advanced computational algorithm can be approximated by a combination of these two quantum gates, plus some classical ones. In practice, however, one first needs a physical machine capable of reliably working with qubits.

A qubit can be made from any quantum two-level system: atoms or ions with two accessible energy levels, particles spinning one direction or the other, photons polarized horizontally or vertically, and so on. To compute with such a qubit, the two levels must be interchangeable via technological manipulation, such as a laser pulse. In the case of Los Alamos's partial quantum computer, called a quantum annealer, the qubits are built from superconducting loops whose two states are electrical currents circulating one direction or the other, manipulated magnetically with a device called a Josephson junction.

Quantum annealing has been shown to perform well for optimization problems, as in graph theory and related search problems, including searching a database, and in other calculations that can be readily mapped into optimization problems. It does not appear to be as promising for better-known, true quantum-computing problems, such as codebreaking and, perhaps unsurprisingly, modeling physical systems that are dominated by quantum effects.

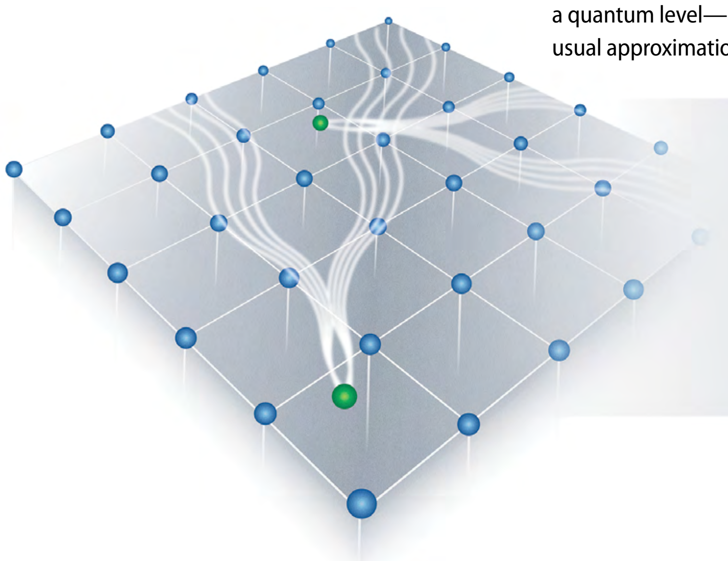
Somma is designing quantum-computing algorithms for complex material simulations, including the well-known Hubbard model. The model describes at a quantum level—as contrasted with the usual approximations, which gloss over quantum interactions—the properties of a lattice of atoms in which some electrons are able to move from one atom to the next. It is an excellent model for electrical conductivity and, importantly, superconductivity. In particular, it may help explain a phenomenon called high-temperature superconductivity, which could allow for the construction of loss-free circuits and transmission lines, presently possible only at low temperatures obtained with cryogenic laboratory equipment. (The quantum annealer itself relies on a sophisticated series of cryogenic "fridges" to isolate its superconducting qubits at one hundredth of a degree above absolute zero.) And Hubbard-model computations of high-temperature superconductivity may be forever beyond the domain of classical computers.

"The best classical supercomputers today can only handle maybe 40 electrons in a Hubbard model lattice—40 qubits on a quantum computer," says Somma. "And even if we allow the computing time of that classical computer to double, we would probably only gain the equivalent of one additional qubit." By contrast, the quantum annealer at Los Alamos processes about 1000 qubits (although it is limited in which gates it can apply to them), and a future quantum computer, it is hoped, would process several million.

Somma is busily preparing for that day, developing quantum-computing algorithms that can be made either with a complete set of quantum gates or with a partial set of quantum operations, as in quantum-annealing applications. He is identifying which problems can be solved efficiently by quantum annealing—including, he found, certain linear algebra computations and simulations of low-temperature but nonquantum physical systems. Meanwhile, the "quantum algorithm zoo," an online compilation of known quantum-computing algorithms put forward by a colleague of Somma's, stands at about 60-strong and growing.

"It's an exciting time," says Somma. "Some of these are likely to be real game changers." LDRD

—*Craig Tyler*



Perhaps not surprisingly, quantum phenomena, such as the interactions between conducting electrons in a solid, are best calculated by a quantum-computer algorithm.

SNAPSHOTS 75 FROM THE HILL

COMPUTERS & COMPUTATION

MISSION, TRADITION, AND DATA REVOLUTION

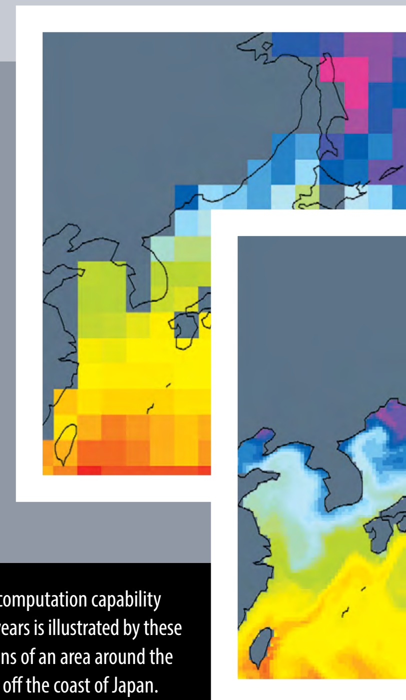
Los Alamos has a rich legacy of leading computing revolutions, a legacy that began before computers even existed. The elaborate calculations underpinning the Laboratory's original mission often took months, so in the race against time, when every day mattered, new methods of streamlining were continually devised. Those efforts—both mechanical and mathematical—paid off and secured permanent places at the Laboratory for computers and computation, which have evolved in tandem over the decades.

Today the Lab is on the leading edge of a new revolution, born of opportunity. With myriad digital devices now cheaply available, mass quantities of data are being produced, and scientists realized that new ways of managing data are needed and new ways of utilizing data are possible. Thus the field of data science was born. Data science at the Lab falls into two broad categories: pattern recognition-based platforms, such as real-time traffic-navigation assistants or cyber-security software, that evaluate risks, rewards, and characteristic behavior; and physics-based platforms that match models and equations to empirical data, such as how fluids flow through fractures in the earth's subsurface during processes like fracking or underground nuclear detonation.

Presently, Los Alamos data scientists are making advances in machine learning, such that data itself can be the algorithm, instead of a human-coded algorithm. The data come from experiments, for example materials-science experiments geared toward building a better widget. First, the computer mines the data to figure out what characteristics comprise a better widget, then it explores avenues to arrive at the best widget possible. Human brains are still required to evaluate performance, but the goal is for even this to be automated.

On the other side of the Lab's computing coin lies simulation, a computing revolution born long ago from brute force and necessity. War and defense have long driven human innovation, and as the Lab transitioned from a temporary war effort to a permanent scientific institution, its first electronic computer, MANIAC I, was built to help model thermonuclear processes for new weapons designs. Built in 1952, MANIAC I used von Neumann architecture, an organization scheme envisioned by Manhattan Project scientist John von Neumann. Overseeing MANIAC I was Nicholas Metropolis, who, along with von Neumann and others at Los Alamos, devised the Monte Carlo method—a computational algorithm based on repeated random sampling rather than direct deterministic computation—which spawned a family of methods that remain essential to modern science.

Contemporary with von Neumann and Metropolis were Enrico Fermi, John Pasta, Stanislaw Ulam, and Mary Tsingau, who together are credited with the birth, in 1955 at Los Alamos, of experimental mathematics and nonlinear science. The Fermi-Pasta-Ulam-Tsingau publication (Mary Tsingau, the programmer who coded the first-ever numerical simulation experiments on MANIAC I, was initially excluded from the byline of the publication) describes a paradox in which complicated physical systems exhibit periodic behavior despite predictions



Improvement in computation capability over the past 25 years is illustrated by these climate simulations of an area around the Kuroshio current, off the coast of Japan.
CREDIT: Mat Maltrud/LANL

to the contrary. The scientists initially thought the computer got it wrong, but then they realized it was their thinking that was off, not the computation. It was new physics. It was unexpected and non-intuitive, and it could not have been done without a computer.

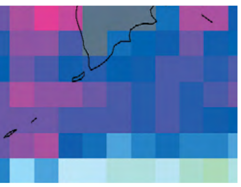
As long as supercomputers have existed, Los Alamos has been home to the latest and greatest among them. After MANIAC I came the IBM 701, the first electronic *digital* computer, followed by the faster IBM 704, then MANIAC II, then the IBM 7030, or "Stretch," which is often

Revolution in computing is a tradition at Los Alamos and is central to the Laboratory's mission.

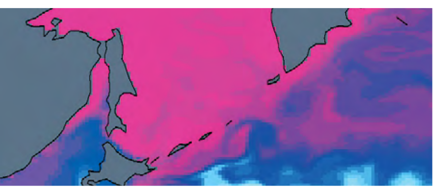
hailed as the first true supercomputer. Continual innovation in supercomputers over the last six decades has enabled continual innovation in simulation, which, although it began with thermonuclear processes, is now at the heart of many different research efforts at the Lab. For example, numerical models used to predict long-term climate shifts as well as weather (e.g., hurricane trajectories) rely on high-performance computing capabilities. Thirty years ago, the best these simulations could do was to parse the weather geographically down to 200-kilometer squares; now they have gotten down to just 10 kilometers.

Although data science and machine learning are the young new arrivals, supercomputing and simulation are the mainstays of the Laboratory's high-performance computing program, and all have their place at the table. By addressing the most complex processes in some of the hardest problems facing science, national labs like Los Alamos are pushing the frontier of science and contributing directly to national security and the global economy. The next milestone on that frontier is exascale computing, the ability to perform a quintillion calculations per second. It's a tall order and a considerable leap from where we are now, but looking back on where we came from, there's every reason to have confidence that Los Alamos will have a leading role in this revolution as well. LDRD

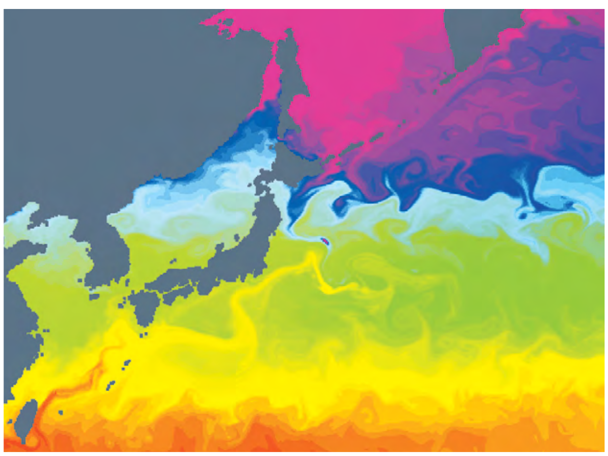
—*Eleanor Hutterer*



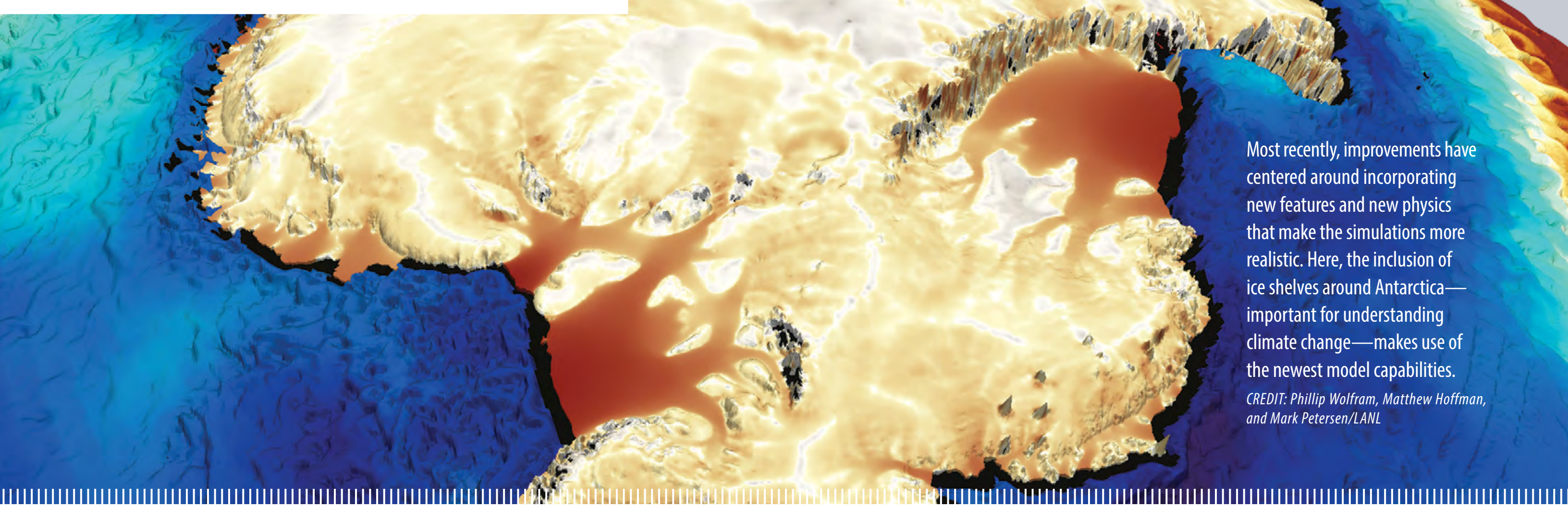
In the 1980s, prior to Los Alamos engaging in climate-simulation research, the best resolution was 2.0 degrees, or about 200-kilometer squares.



In the early 1990s, the Connection Machine, a resident supercomputer, helped bring the resolution down to 0.28 degree, or about 30-kilometer squares. This simulation was presented to President Clinton during one of his visits to the Laboratory and also won a Smithsonian Computer World award.



In the 2000s, additional evolution of supercomputer hardware and architecture enabled the resolution to reach 0.1 degree, or 10-kilometer squares.



Most recently, improvements have centered around incorporating new features and new physics that make the simulations more realistic. Here, the inclusion of ice shelves around Antarctica—important for understanding climate change—makes use of the newest model capabilities.

CREDIT: Phillip Wolfram, Matthew Hoffman, and Mark Petersen/LANL

CREDIT: Michael Pierce/LANL

IN THEIR OWN WORDS

Los Alamos historian **ALAN CARR** wonders if he might just have the best job at the Laboratory.

ON MANY OCCASIONS, OFTEN DURING HISTORICAL TOURS or after briefings, I've had co-workers make the comment, "Alan has the best job at the Laboratory!" Most days, that may very well be true. But what are most days like? How does one become a Laboratory historian anyway? Why does a scientific laboratory even have an historian? These are all questions I've often received, but I don't recall ever formally answering them—until now.

I started working as an historian at Los Alamos in May 2003 at the ripe, historical age of 25. I had recently finished my master's thesis on Soviet military doctrine and was lucky to have stumbled upon the job ad on the American Historical Association's web site. Virtually every time I introduced myself as an historian, I would hear some variation of the following: "You're too young to be an historian," or, "I imagined the Lab historian would be ancient and have a beard!" John C. Hopkins, former head of the Los Alamos weapons program, once quipped, "You know, the odds of winning the lottery are far better than the odds of getting your job." He was right. I feel lucky to have this unique job, and one of the reasons why is because the Lab is rich with 75 years of fascinating history.

75 years of innovation

The Los Alamos story begins in early 1943, when Nazi Germany and Imperial Japan ruled much of the globe. Los Alamos was founded to design, build, test, and help deliver the world's first nuclear weapons. Only 28 months after the Laboratory's first major technical conference, two entirely different types of nuclear weapon were successfully delivered in combat against the Japanese cities of Hiroshima and Nagasaki. Days later, the Japanese Government surrendered unconditionally, bringing one of history's deadliest conflicts to an abrupt and victorious conclusion.

THE ARCHIVES CONTAIN ABOUT 20,000 REELS OF MOTION PICTURE FILM, 1,000,000 PHOTOGRAPHIC NEGATIVES, AND 8,500 VIDEOTAPES.

Given this illustrious origin, it was probably my background in Russian history, specifically that of the Red Army up through World War II, that helped me secure this historian job. And I'll admit, I do have a soft spot in my heart for World War II-era books, movies, and memorabilia; my office is filled with them. However, the way that the Lab changed after the War, and how each scientific innovation it produced branched into another, is fascinating and continues to pique my interest on a daily basis.

For instance, in the 1950s, as weapons research continued in the shadow of the Cold War, Laboratory scientists began developing nuclear rocket engines to propel missiles. However, when the technical landscape changed—because miniaturized weapons could be delivered with chemical rockets—the nuclear rocket program instead began to fuel new research in space technology. This branching evolution of innovation and technology happens again and again throughout the Lab's history.

Space research at Los Alamos has often had a dual purpose. For example, the Partial Test Ban Treaty, a diplomatic milestone between the United States and the Soviet Union, was made possible by the advent of the Los Alamos-designed Vela satellites. And though intended primarily to surveil the globe for clandestine nuclear tests, a Vela satellite serendipitously discovered gamma-ray bursts from deep space in 1967.

Computing at Los Alamos has also evolved to support many types of research. When underground nuclear testing ended in 1992, Los Alamos turned to its own expertise in computer simulation—which began with the invention of MANIAC I, built in 1952— to help with "science-based stockpile stewardship." But supercomputers enable many other types of work at the Lab, including vaccine development, climate modeling, probing the early universe, and modeling antibiotic resistance and the spread of disease.

The list of exciting science could go on and on. Los Alamos made major technical contributions to the Strategic Defense Initiative, established the public gene database GenBank, was a leader in the Human Genome Project, detected the neutrino, was a pioneer in fusion energy and quantum cryptography, and built two of the world's most powerful lasers, *Antares* and *Aurora*. For 15 years I've been reading about the achievements of the past and present, and yet there is always something new and exciting to learn.

Day in the life

When I first came to Los Alamos, I worked in the old records center. Except for my office, which overlooked the loading dock, the entire building was a vault. I spent my first several months learning the history of the Laboratory in my loading-dock office. I gradually fell in love with the rich history of the Laboratory and with my new, absolutely breathtaking home state. Sadly, I soon had to surrender my coveted window office and move inside the vault, where I shared an interior office with John Hopkins.

After I completed all the appropriate training, my predecessor Roger Meade gave me free reign to do research in the archives. Back then the plan was to write the grand history of the Laboratory's Cold War years, but for a variety of reasons, that never materialized. As I became more knowledgeable by completing less ambitious projects, I was entrusted with responding to public inquiries for information. Our team receives questions from all over the world every week. Perhaps the most common question we get is: "When did Los Alamos Scientific Laboratory become Los Alamos National Laboratory?" The answer: January 1, 1981. Easy, but perhaps not very interesting. On the other hand, John Hopkins was on the receiving end of my favorite request of all time. The Laboratory's legendary third director, Harold Agnew, who had quite a shrewd sense of humor, called John and asked: "Hey, was I at the Trinity test?" Harold explained that he was not at the world's first nuclear test, but that Luis Alvarez's memoir said otherwise. I think Harold was hoping we could

From the archives: Nuclear rockets were tested at the Nevada Test Site from the 1950s until the early 1970s. The test pictured here was significant in that it confirmed vibration was the primary cause of failure in a previous test, in which a reactor shook itself apart. These tests were important stepping stones on the road to the Phoebus-2A reactor. On June 26, 1968, the 2A ran for 12 minutes and reached a peak power of 4080 megawatts, making it the most powerful individual reactor of any type ever built.

figure out how Luis had gotten the story wrong—since Harold had instead been in the South Pacific, helping to prepare combat weapons at the end of the war—but we never did figure out that mystery.

Writing history is a labor of love, but the government isn't a big fan of funding labors of love. I've also discovered most people aren't interested in reading esoteric pieces of history. For example, many years ago, I published a short biography on the first head of the Physics Division, Robert F. Bacher. You can find my book on Bacher and Bacher's obituary of J. Robert Oppenheimer at the Los Alamos History Museum gift shop. A while back, my late and excellent friend David Mullen purchased a copy of my book, which prompted the cashier to state, "I've sold several books by Bacher, but never this book about him." Such is the nature of much historical writing, and mine is no exception.

Although few have really sat down to read my writings, many people have attended my historical talks. Public speaking has become a favorite part of the job, but it hasn't always been that way. Back in 2004, when I had been on the job less than a year, I did my first on-camera interview for a History Channel

I GET TO KNOW PEOPLE FROM ALL OVER THE LABORATORY, THE NATION, AND THE WORLD.

program called *Man, Moment, Machine*. I was so nervous that I had to take a vomit break in the middle of the interview. I'm not a natural speaker. Is anyone? But as I mastered my subject and learned from many, many, many mistakes, I started to enjoy speaking. I still speak beyond my allotted time and tell cringe-worthy jokes, but some habits are difficult to break.

Perhaps the most important part of my job is helping to preserve the documented history of the Laboratory. Although I'm often introduced as the Laboratory archivist, I'm not an archivist. Archivists are more important than historians, because without archivists, historians would not have access to records to manipulate. The archivist of the Laboratory is Norma Baca, and I thoroughly enjoy working with her and our media archivist, John Moore, to preserve our roughly 12,000 cubic feet of permanent records. The collections we maintain include about 20,000 reels of motion picture film, 1,000,000 photographic negatives, 8500 videotapes, and a lot of paper.

Where do our historical records come from? Typically they're transferred to us from originating organizations, but we've retrieved records from basements, garages, automobile trunks, etc. (We make house calls!) Many people assume we continually dwell on the past in the archives, but that's far from true. When we identify records for preservation, we're thinking ahead. What might be useful for the technical staff five, ten, or 50 years into the future? Indeed, some of our oldest records remain our most programmatically valuable.

Even as an historian, I often take our history for granted. Our world-changing institution has captured the imagination of people around the world since our existence became publicly known in August of 1945. We regularly work with the news media, film and documentary makers, writers, academics, and students. I've had the opportunity to spend time with Academy Award winners, Pulitzer Prize winners, cabinet-level secretaries, Nobel laureates, U.S. senators, and even the founder of Microsoft. The reason we at Los Alamos are perennially in the spotlight is because of our history. We are the name brand: we are the Laboratory they make television shows and movies about. And we continue to make history! That's great news, because I'll never run out of history to preserve and showcase.

So, do I have the best job at the Laboratory? Like everyone else, I have to take a lot of training and work under stringent procedures. And spelunking in potentially hantavirus-infested storage sheds and preparing inventories to ship classified records isn't exactly living the life of Indiana Jones, but I have no gripes—except, perhaps, that a window office would be nice. The best thing about being the Los Alamos historian is the hugely diverse set of people I get to know. I meet people from all over the Laboratory, the nation, and the world. Almost every day I meet a new person, learn a new factoid, enjoy a new adventure, and get paid to do it. I don't know if I have the best job at our amazing institution, but it's pretty phenomenal. I certainly don't plan to give it up anytime soon.

—Alan Carr

The Laboratory has been home to many Nobel laureates. But in only one instance was the prize-winning work done during the winner's tenure at Los Alamos. That was in 1956, when Fred Reines and Clyde Cowan proved the existence of a new kind of subatomic particle, the neutrino. Since then, neutrino science has continued at the Lab and elsewhere, leading to three more Nobel Prizes. Now, new experiments at Los Alamos are poised on the brink of a new discovery, which looks to be just as exciting as any of them.

In 1930, theoretical physicist Wolfgang Pauli proposed that a new particle—invisible and uncharged—was needed to satisfy the law of conservation of energy during radioactive decay of atomic nuclei. Pauli used the name "neutron," which was the same name given to another, more massive particle. Pauli's contemporary Enrico Fermi, who would later join the war effort at Los Alamos, resolved the nomenclature problem by giving the less massive particle the Italian diminutive "-ino," and *viola!* The neutrino.

Scientists now know that neutrinos are among the most abundant particles in the universe—hundreds of trillions of them stream unobtrusively though our bodies every second of every day. So far, three varieties are known: the electron neutrino, the muon neutrino, and the tau neutrino. Neutrinos are almost completely inert, interacting with other particles only by gravity and by the weak nuclear force. In fact, Fermi based his original postulation of the weak nuclear force on Pauli's proposed, and still hypothetical at the time, new particle.

In the early 1950s, as the Laboratory was expanding from a war-time weapons lab to an institution with broader interests, Reines and Cowan, spurred by the general consensus that it was impossible, set out to capture the elusive neutrino. Because neutrinos are so inert, the likelihood of one interacting with a detector is remote, so a tremendous number of neutrinos is needed to be able to observe just one. The duo initially intended to use an underground nuclear bomb test as the source of this tremendous number of neutrinos, but they quickly determined that a nuclear reactor would be better, so they took their detector—a rig about the size of a modern washing machine—to the reactor at Hanford, Washington.

After preliminary work at Hanford, the team decided to build a bigger and better detector at the brand new reactor in Savannah River, South Carolina. It was there that they finally and conclusively observed the electron antineutrino—the antiparticle of the electron neutrino, whose very existence proved the existence of the other. Reines and Cowan sent a jubilant telegram to Pauli in Switzerland informing him of their success. Clyde Cowan died in 1974, and Fred Reines alone was awarded the Nobel Prize in 1995 for their work.

Nowadays most neutrino detectors are much, much larger. Usually they are international collaborations involving thousands of tons of liquid in enormous vessels thousands of feet below the surface of the earth. But the latest neutrino detector at Los Alamos, though larger than the first, is still quite small, just three meters tall, and shaped like a pressure cooker.

Reines and Cowan relied on brute force and brilliance, but this latest Los Alamos neutrino detector has the benefit of serendipity as well. It turns out that the proton beam at the Los Alamos Neutron Science Center—established in 1972 to study the short-lived subatomic

Fred Reines (left) and Clyde Cowan inspect their neutrino detector in 1955, a predecessor to the one they used in 1956 to prove the existence of the elusive neutrino. Forty years later and 21 years after Cowan's death, Reines alone was awarded the 1995 Nobel Prize in Physics for their shared discovery.

CREDIT: LANL photo archive

SNAPSHOTS 75 FROM THE HILL
NEUTRINO HUNTING

BRINGING NEUTRINOS BACK TO LOS ALAMOS

Bill Louis (left) and Richard Van de Water inspect their neutrino detector, CAPTAIN-Mills ("CAPTAIN" for Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos, and "Mills" in honor of their colleague and friend, Geoff Mills, who passed away in 2017).

CREDIT: Michael Pierce/LANL

particles known as pions—is an abundant source of neutrinos, which are a natural byproduct of charged pion decay. Also, the three-meter-tall pressure cooker, which was built by a different group in 2014 for an unrelated experiment, was no longer needed and was up for grabs. In 2017, Richard Van de Water and Bill Louis acquired it and are now in the process of converting it into a liquid argon-based detector to prove the existence of an as-yet hypothetical neutrino variant: the sterile neutrino.

Whereas regular neutrinos are *almost* inert, interacting only by the weak force and gravity, sterile neutrinos, if they exist, have to be *completely* inert, interacting by none of the known forces of particle physics, only gravity. For a decade, Louis and collaborators ran the Liquid Scintillator Neutrino Detector experiment at Los Alamos, which, via the same reaction picked up by Reines and Cowan, led to the first experimental evidence of sterile neutrinos. Presently, Louis and Van de Water collaborate on the Mini Booster Neutrino Experiment at the Fermi National Accelerator Laboratory near Chicago, which, by way of a different reaction, has produced even more convincing evidence for sterile neutrinos. The pressure-cooker detector is designed to detect sterile neutrinos in yet a third way: by the oscillation of muon neutrinos into sterile neutrinos, which will look like muon neutrinos disappearing.

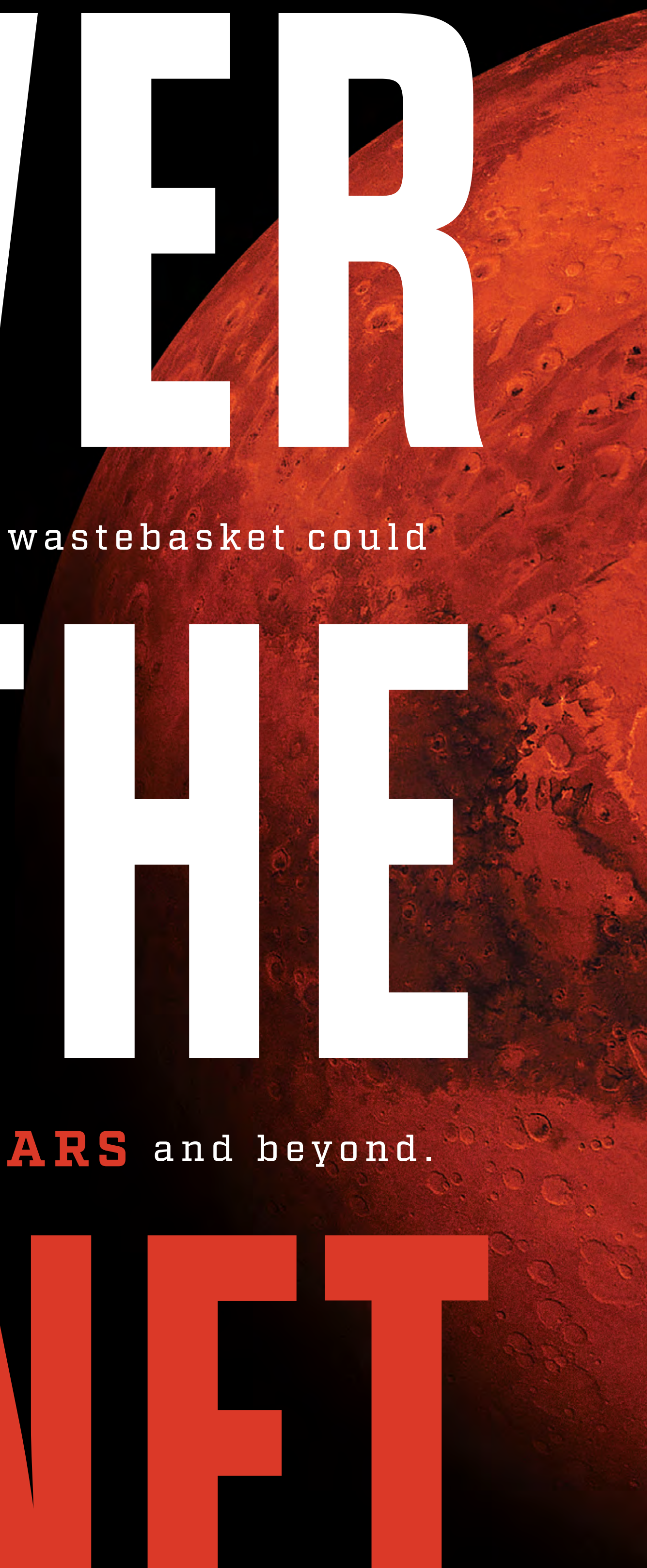
Many scientists thought neutrinos could be important to resolving the dark matter conundrum—i.e., what it is and how it works—but the mystery persists. Now the idea of sterile neutrinos is tantalizing as a possible portal to the dark sector. If sterile neutrinos really do exist, it will be the biggest thing in subatomic physics since the quark. If not, it will still be a big deal, because whatever Louis and Van de Water are measuring, it's not nothing. It's definitely something.

There is a shared sense among physicists that there is not-yet-discovered physics at hand, and everyone is drilling in a different place to find it. Louis and Van de Water are drilling at the place where medium-energy muon neutrinos can transform into sterile neutrinos. They've seen it with two different experiments so far, and they're going for a hat trick.

Some say it can't be done. That it's impossible. But then, they've said that before. LDRD

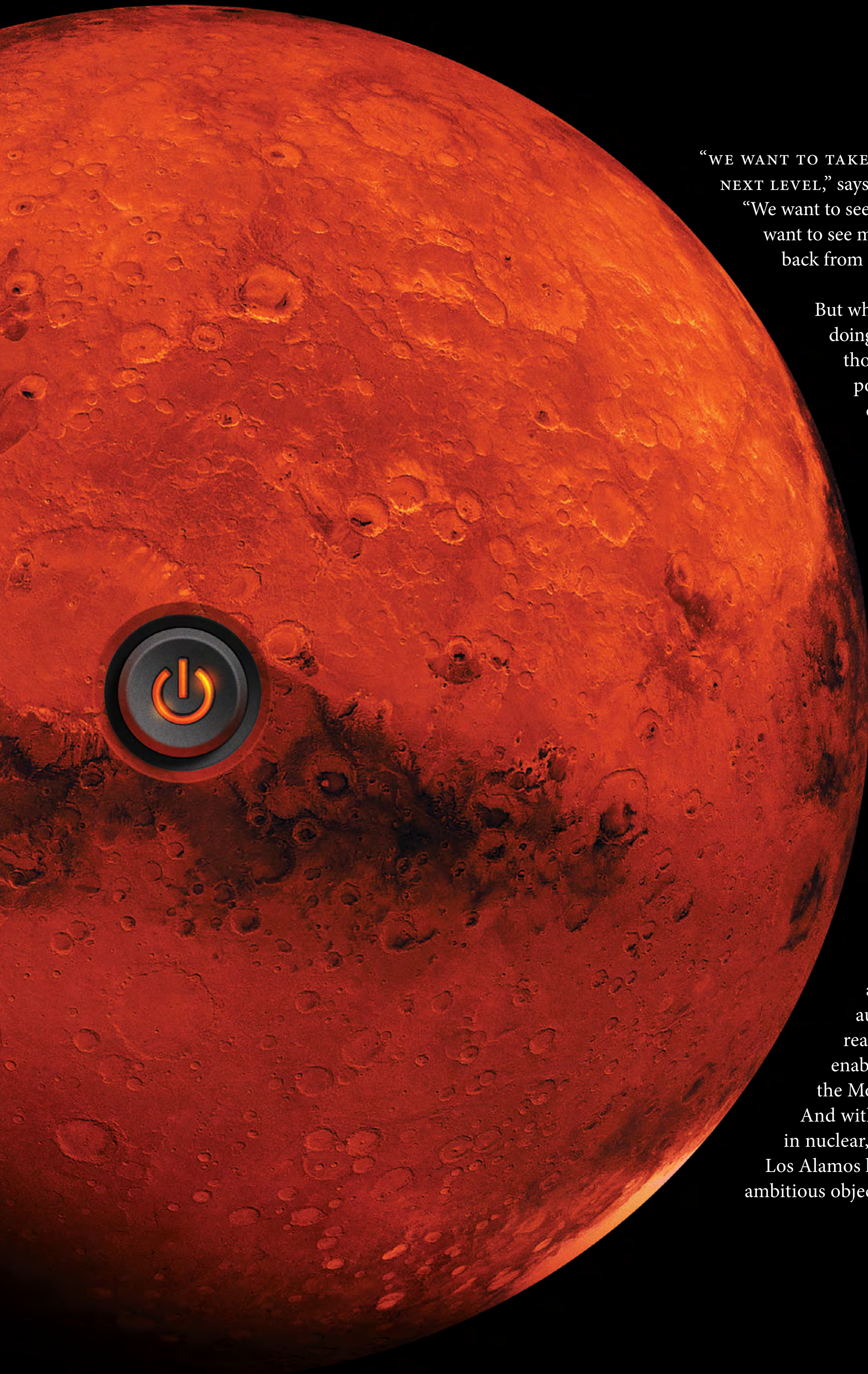
—*Eleanor Hutterer*

Los Alamos scientists were the first to detect neutrinos. Now a new batch of scientists is going after a new kind of neutrino, even harder to find than the first one.



POWER TO THE PLANET

A nuclear reactor the size of a wastebasket could power future operations on **MARS** and beyond.

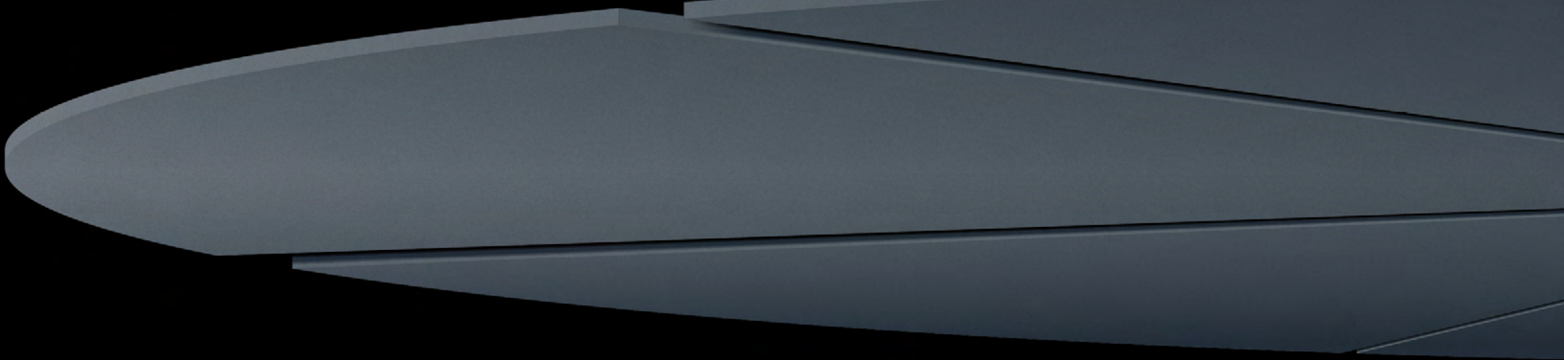


"WE WANT TO TAKE SPACE EXPLORATION TO THE NEXT LEVEL," says Los Alamos engineer David Poston. "We want to see human habitation on Mars, and we want to see much more scientific data coming back from our deep-space probes."

But when it comes to space exploration, doing more always traces back to the thorny problem of generating more power, and for human habitation on Mars or even our own Moon, a *lot* more power. Unfortunately, the intensity of sunlight on Mars is less than half of what it is on Earth, and darkness and dust make solar power a severely limited option. Beyond Jupiter, it's basically not an option at all.

Fortunately, a solution may finally be at hand: the "Kilopower" nuclear-fission reactor. It is the present incarnation of an idea that Los Alamos has been considering for decades. Poston, the lead designer, and Patrick McClure, the Los Alamos project lead, have recently returned from the Nevada desert, where they successfully tested their concept: a wastebasket-sized and fully autonomous space-based nuclear reactor. McClure and Poston hope to enable nuclear power stations for Mars, the Moon, and the outer solar system. And with a long history of innovation in nuclear, space, and energy technology, Los Alamos has the pedigree to transform this ambitious objective into reality.

CREDIT: NASA/JPL-Caltech/USGS



Two rovers are currently operating on Mars, *Opportunity* and *Curiosity*. *Opportunity* arrived in 2004. It was only expected to last about 90 days, after which the five-month Martian winter would have permitted too little sunlight to reach its solar panels, but NASA was able to tilt the rover sufficiently toward the sun to keep it alive and well eight Martian winters later.

Out of the box, *Opportunity* could recharge its batteries with 900 watt-hours of power per day from its solar panels (enough to put out 100 watts for nine hours, for example). In the winters, this often dropped to about 300 watt-hours—barely more than what the rover needs just to remain "awake"—severely limiting what, if anything, the rover could accomplish between solar recharges. Complicating matters, solar panels degrade over time, and dust storms can obscure the sun for weeks or months.* (Poston points out that even in good weather, Matt Damon would have needed about 100 times as many solar panels to provide the power he used in the movie *The Martian*.)

By contrast, the *Curiosity* rover, which landed in 2012, runs on nuclear power via a device known as a radioisotope thermoelectric generator (RTG). It uses the prolific radioactivity of plutonium-238 from Los Alamos to produce heat, which is then converted to electricity by a low-efficiency but long-lived and reliable thermoelectric device. Since plutonium's half-life is 88 years, the RTG will continue to function for a long time, although its power decreases each year as the plutonium decays. But it's no simple matter to manufacture and launch large quantities of plutonium, and *Curiosity's* RTG, even when new, was limited to only 110 watts. Indeed, interplanetary spacecraft are typically limited to only a few hundred watts of RTG-supplied power.

THE REACTOR WILL PUT OUT AS MUCH HEAT AS IS ASKED OF IT

Whether for a rover or a spacecraft, making the most of such limited power is a serious challenge. *Opportunity* and *Curiosity*—extraordinary successes by any measure—have traveled 28 and 12 miles, respectively, in all the years they have been operating. But what if NASA wanted to explore significantly farther afield or do more energy-intensive science each day? Realistically, existing power systems for robotic exploration are already pretty close to maxed out.

Then what about a human habitat on Mars? How much power would that require? At its peak, a typical U.S. household might consume 5000 watts (or 5 kilowatts, kW) just by running the lights and appliances and maintaining a temperature slightly more comfortable than the natural temperature range on Earth. But a Mars habitat would have to provide heat against a –55°C average surface temperature; recharge rovers capable of carrying astronauts and their gear over large distances; and manufacture air, water, and rocket fuel from native resources. Experts estimate that a habitat on Mars would need a reliable source of 40 kW or more. To accomplish this with solar power, for example, would require an extremely large mass of solar panels and batteries and would be limited to locations close to the Martian equator. By contrast, fission power is lighter and would be reliable in any geographical location, day or night, in clear skies or even massive dust storms.

Portable power plant

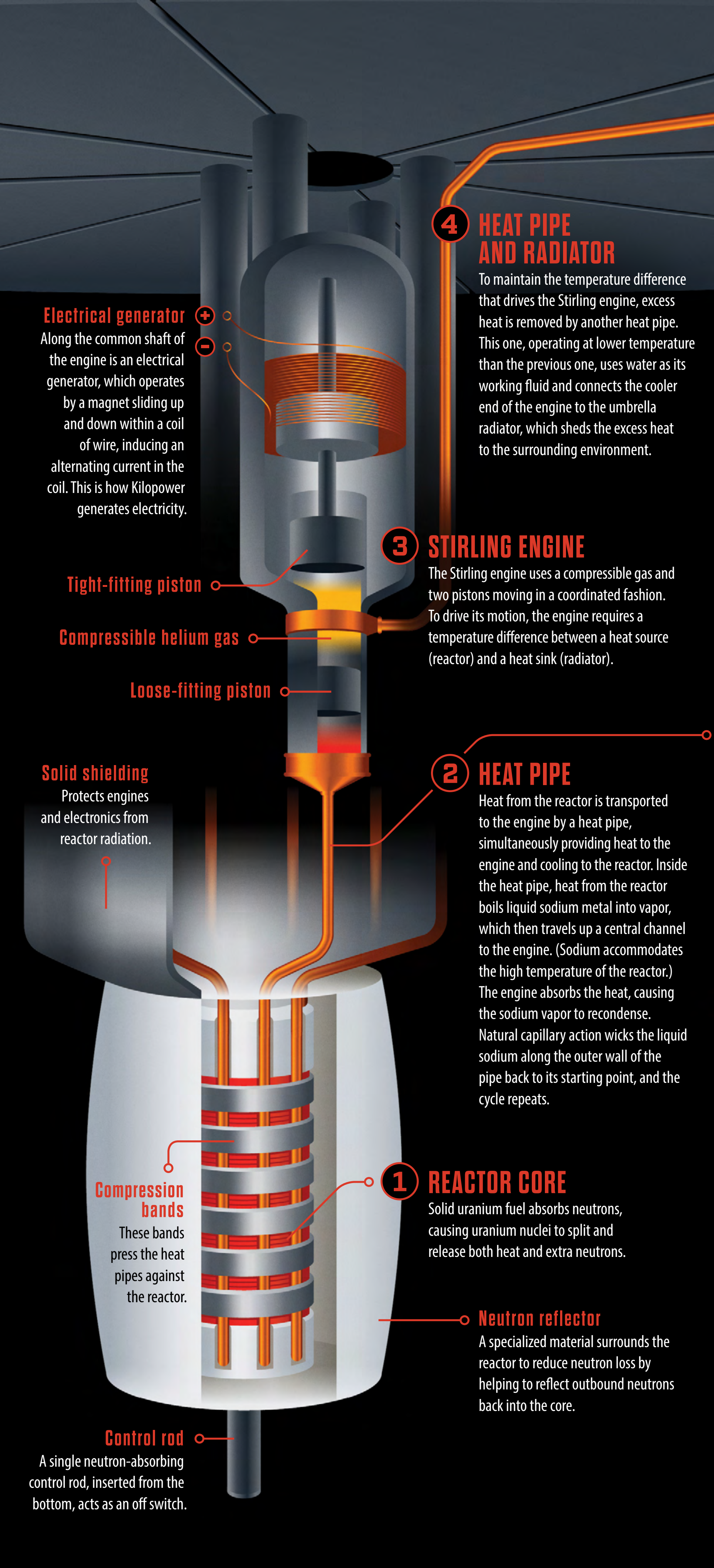
McClure and Poston's reactor recently demonstrated what five decades of research and experimentation had yet to do successfully: operate a nuclear fission power plant—think giant cooling towers—that's lightweight, reliable, and efficient enough to run fully automated without refueling for a decade or more in a hostile environment. Instead of producing about a gigawatt (a billion watts) like a nuclear power plant on Earth, two Kilopower designs produce either 1 or 10 kW. A single 1-kW unit would greatly outclass existing RTG power systems on large, unmanned, interplanetary spacecraft like *Galileo* or *Cassini*. And a human habitat on Mars, as currently envisioned, would run four of the 10-kW variety and keep a fifth one in reserve.

A nuclear power plant basically has four components. (1) A nuclear reactor generates heat by fission, or "splitting the atom." (2) A heat exchanger, which is effectively a plumbing system, carries the heat away from the reactor and delivers it to an engine, simultaneously powering the engine and cooling the reactor. (3) The engine uses the heat to boil a liquid, as in a steam engine, or expand a gas, as in a jet engine, to turn a turbine or move a piston. That motion drives a generator to produce electricity. (4) Another heat exchanger then carries residual heat away from the engine and offloads it to the surrounding environment. For Kilopower, steps (1) and (2) pertain to the Los Alamos reactor design; the others pertain to the NASA power conversion system, which NASA engineers successfully designed and integrated with the reactor.

Counting backwards, cooling technology (4) is relatively straightforward, and for Kilopower, it is accomplished by

*As this publication goes to press, the *Opportunity* rover's fate is uncertain because a massive, planet-wide dust storm—raging for seven straight weeks as of mid-July—is severely limiting the available solar power.

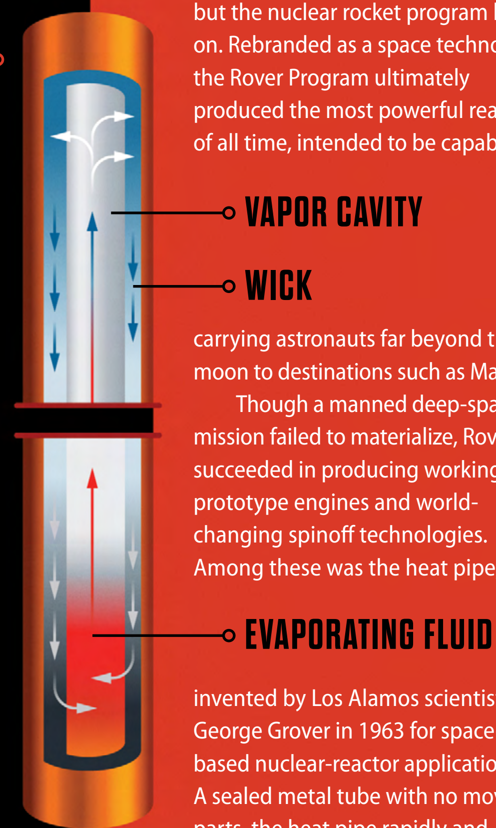
HEAT CONTROL FROM THE COLD WAR



With the emergence of the Cold War, the Laboratory's postwar future began to solidify. In the 1950s, Los Alamos conducted the world's first full-scale thermonuclear test, and as a means of delivering such large, first-generation thermonuclear weapons, it started developing nuclear rocket engines to propel missiles. The need for nuclear-propelled missiles quickly faded as the Laboratory miniaturized nuclear weapons so that they could be delivered with chemical rockets, but the nuclear rocket program lived on. Rebranded as a space technology, the Rover Program ultimately produced the most powerful reactor of all time, intended to be capable of carrying astronauts far beyond the moon to destinations such as Mars.

Though a manned deep-space mission failed to materialize, Rover succeeded in producing working prototype engines and world-changing spinoff technologies. Among these was the heat pipe, invented by Los Alamos scientist George Grover in 1963 for space-based nuclear-reactor applications. A sealed metal tube with no moving parts, the heat pipe rapidly and reliably conveys heat from one end to the other without an external power source.

—Alan Carr



delivering excess heat to a thin metal "umbrella," which radiates the heat away. Step (3) requires a lightweight, maintenance-free engine system to operate on Mars, rather than the likes of a massive, pressurized steam engine, as on Earth. For this, McClure, Poston, and their collaborators at NASA prefer Stirling-engine technology, which NASA has been developing for decades because of its simplicity and efficiency. An engine converts energy from heat (from burning coal, a solar concentrator, nuclear fission, etc.) into motion, and the Stirling variety uses a loosely fitted piston surrounded by a compressible gas in a sealed cylinder—requiring fewer moving parts than, for example, a car engine, in which valves must repeatedly open and close to intake fuel and air and discharge exhaust gas.

A KILOWATT UNIT WOULD GREATLY OUTCLASS EXISTING POWER SYSTEMS ON LARGE INTERPLANETARY SPACECRAFT LIKE GALILEO OR CASSINI

A key innovation that allows nuclear fission to become spaceworthy is the heat exchanger (2) between the reactor and the Stirling engine. Rather than using conventional plumbing—susceptible to corrosion and requiring fluids (which could leak) propelled by power-consuming pumps (which could fail)—it uses something called a heat pipe. Invented in 1963 for space-based reactor applications by Los Alamos scientist George Grover, with experimental work carried out by his Laboratory colleagues Ted Cotter and George Erickson, the heat pipe is a sealed metal tube with no moving parts. A liquid—molten sodium in the case of Kilopower—is boiled into vapor at the hot reactor end of the pipe and then travels to the comparatively cold end, where it provides the heat source for the Stirling engine. There it re-condenses and, through natural capillary action, flows back to the hot end. Such heat pipes are reliably long-lasting and consume no power to operate.

Fission fired and fully fail-safe

Finally, there's the fission reactor (1). Kilopower's fuel, like that of Earth-bound nuclear plants, is uranium-235. Fission of uranium-235 happens when the nucleus absorbs a neutron, causing it to split into two smaller atomic nuclei, plus a few more neutrons. Poston's design uses a solid, cast uranium core the size and shape of a coffee can. Wrapped around it is a layer of beryllium oxide to help reflect outbound neutrons back into the core, where they can induce more fissions. There is also a control rod made of boron carbide, which absorbs neutrons, inhibiting the chain reaction. It acts as a power switch: when the rod is withdrawn, the reactor turns on; when the rod is inserted, the reactor shuts down.

The reactor is designed to be fully autonomous. Unlike nuclear power plants on Earth, with control rooms staffed with nuclear engineers, Kilopower adjusts power on its own as conditions require. Importantly, it does this entirely through passive responses, meaning that it is controlled directly by the laws of physics, rather than by a computerized control system, which could malfunction.

For instance, for Kilopower's equivalent of a loss-of-coolant accident (a serious failure for a nuclear power plant on Earth), the rising temperature in the reactor core causes the fuel to expand. This, in turn, reduces the core's density, thereby allowing more neutrons to escape and correspondingly decreasing the fission rate. Essentially, the reactor senses—without relying on sensors—that it is overheating and immediately cuts power. Conversely, if power is being consumed too quickly, the heat draw of the Stirling engine increases, so the reactor core cools, becomes denser, and therefore produces more fissions to adjust to the increased power draw.

Artist's conception of Kilopower on Mars with umbrella-style radiators fully deployed.
CREDIT: NASA Langley

“Whether during normal operation or some kind of fault, the reactor will put out as much heat as is being asked of it,” says Poston. “Even if the Stirling engines stop completely, the reactor will not overheat. It will wait in warm standby, ready to produce full power if the engines restart.” The robust design eliminates the potential hazard of a meltdown, although Poston notes that, for an astronaut, loss of power may be a bigger concern than any potential radiation release.

There is also minimal danger on Earth. Unlike RTG plutonium, which is highly radioactive, uranium-235 has comparatively little radioactivity. So even if a rocket intended to carry a Kilopower unit into space were to explode during takeoff, spreading uranium across land or sea, the radiation hazard would be essentially negligible—hundreds of times less than what the average American receives in a year from natural sources.

Once the reactor is up and running, the uranium splits into other isotopes with greater radioactivity, but that takes place in space or on Mars, not here on Earth. And while constructing anything with the potential for sustained fission obviously demands that significant safety and security protocols be observed, it doesn’t carry the kind of risk already sufficiently minimized to be approved for RTGs.

THERE’S VERY LITTLE SUNLIGHT DURING THE LONG MARTIAN WINTER—OR DURING MONTH-LONG DUST STORMS

Los Alamos legacy

The heart of Kilopower’s technology is quite old: the Stirling engine was invented in 1816, the first nuclear reactor was built in 1942, and the heat pipe, in its Los Alamos conception, was patented in 1963. But successful integration at small scale and with spaceworthy technology and autonomy has proven elusive for decades. An American experimental fission-powered satellite was launched in 1965, but its active-control system failed within a month and a half, and that was that for American fission power in space for decades thereafter.

Recent presidential administrations have indicated the desire to send humans back to the Moon and subsequently to Mars, putting fission power in space back on the table. (Nearly everywhere on the Moon is in shadow for weeks at a time, making solar power impractical, despite the solar flux being about as strong there as it is on Earth.) Still, NASA remained leery of pursuing fission power because of the expensive failed programs of the past, giving McClure and Poston the chance to seize an opportunity.

“In 2012, we came up with the idea of a very simple reactor demonstration to prove to NASA—and frankly to ourselves—that we could test a small-reactor concept quickly and affordably,” says McClure. “We leveraged an existing experiment and the expertise of the Los Alamos team at NCERC,” he says, referring to the National Criticality Experiments Research Center at the Nevada National Security Site (NNSS). The NNSS, which has the facilities and security measures in place to accommodate work involving enriched nuclear fuels, is also where Los Alamos researchers perform subcritical experiments on key nuclear-weapons components.

The success of the 2012 demonstration convinced NASA to test something much closer to a prototype reactor. That full-temperature test took place earlier this year at the NNSS, with the reactor behaving as predicted and meeting all major test objectives. It convincingly proved—for the first time since their conceptualization in the 1960s—that heat-pipe-cooled reactors offer predictable and robust performance. (Poston called the 2012 demonstration “demonstration using Flattop fissions,” or DUFF, and the 2018 one “Kilopower reactor using Stirling technology,” or KRUSTY; he readily admits to a bit of *Simpsons* fandom.)

“DUFF and KRUSTY were the first heat-pipe reactors ever built,” says McClure. “And we at Los Alamos have the unique history that helped bring it all together. From our fundamental research on nuclear technology in the Manhattan Project to our subsequent research on nuclear rockets and satellites and heat pipes and RTG fuel, we are now working to enable a new era in space.”

“But it’s more than just our history,” Poston adds. “This work would not have been possible without the unparalleled nuclear-computation codes, physics data, and experimental capabilities that the Laboratory maintains today.”

Following on the successful KRUSTY experiments, Kilopower stands ready for a spaceflight demonstration and subsequent full-scale deployment. But the technology admits even grander, longer-term possibilities, too. Kilopower could someday become megapower.

“We could ultimately scale up to millions of watts, and who knows what that would do for humanity’s future in space?” ponders McClure. “In many respects, scaling fission *down* is the harder thing to do.” LDRD

—*Craig Tyler*

More **nuclear technology** at Los Alamos

http://www.lanl.gov/discover/publications/1663/archive.php

- **Subcritical nuclear tests at the NNSS**
  “The Bomb without the Boom” October 2017
- **Nuclear data from neutron-capture experiments**
  “The Other Nuclear Reaction” May 2017
- **Low-cost pathway to fusion power**
  “Small Fusion Could Be Huge” July 2016
- **The DUFF reactor demonstration**
  “Interplanetary Mission Fission” July 2013

FROM TRASH TO 100-TESLA TREASURE

SNAPSHOTS 75 MAGNET LAB FROM THE HILL

Inside a strange building with five-foot-thick concrete walls and six-foot-diameter portholes resides a family of magnets unlike any others in the world. This is the Pulsed-Field Facility (PFF) at Los Alamos, a paragon of ingenuity and one of three facilities that comprise the National High Magnetic Field Laboratory, (the Magnet Lab). The building itself was inherited from another project, hence the anachronistic portholes. So too was the enormous motor-generator that powers the magnets from the more conventional building next door. This generator, once dormant and destined to be scrapped, is what makes the record-setting magnetic fields at this world-class research facility possible, though it was never intended for this purpose.

In the mid 1980s scientists at Los Alamos were planning a new facility, the Confinement Physics Research Facility, to study nuclear fusion. The project required strong magnetic fields, which in turn required a very large power source for the intended electromagnets. Unlike permanent magnets, electromagnets are transient and are only magnetic when powered by electricity. After scouring the country, the scientists happened upon a giant sleeping in a Tennessee field, near the banks of the Cumberland River.

The behemoth lay in pieces inside a warehouse, its life seemingly over before it had begun. The nearly 700-ton Swiss-made steam turbine generator was one of several that had been purchased new a decade earlier by the Tennessee Valley Authority for the planned, and then abruptly canceled, Hartsville Nuclear Plant. Never even assembled, it was sold to Los Alamos for little more than the price of scrap.

The 1200-mile journey west began in 1987 and required numerous feats of engineering, as the generator, weighing about the same as four large blue whales, was the heaviest single load ever to travel on New Mexico roads. First, the stator and the rotor, the two largest pieces of the generator, were repacked into their original crates and loaded onto a barge, which traveled down the Cumberland River to the Ohio River, then by way of the Mississippi River to the Arkansas River and into Catoosa, Oklahoma. Next, the crates were loaded onto special train cars custom built for the second leg of the voyage, a convoluted rail route dictated by bridge weight restrictions, to Lamy, New Mexico. Finally, in the spring of 1988, the generator completed its journey with much fanfare, traversing the 65 miles from Lamy to Los Alamos by road, in a slow-moving convoy that drew crowds, closed roads, and used special temporary bridges and load spreaders for the 17 bridge and culvert crossings along the way.

Bizarrely, no sooner was the enormous generator finally installed in its brand new building, than the plasma confinement project, like the nuclear power plant, was abruptly canceled. It was late 1990 and the rotor had been turning for one week.

Meanwhile, elsewhere on the Hill, discussions were under way about Los Alamos joining a National Science

The nearly abandoned and still new motor generator leaves Tennessee on a barge, headed for the big-time at a new plasma-confinement facility in New Mexico. *CREDIT: MagLab photo archive*

Foundation collaboration, as the site of a new pulsed-field facility for the Magnet Lab. One aim of this proposal was to build the first long-pulse 60-tesla magnet. (A tesla is a large unit of magnetic field strength; even a hospital MRI usually

The Pulsed-Field Facility draws scientists from around the world to Los Alamos.

Despite the plasma-confinement gig falling through, the motor generator has indeed found fame and glory as the source of power for world-record-setting magnets at the National High Magnetic Field Laboratory's Pulsed-Field Facility. *CREDIT: Michael Pierce/LANL*

operates at only 3 tesla). Among the Laboratory's assets were an essentially new generator, recently orphaned and ready to power the proposed 60-tesla magnet, and a robust body of expertise in explosives-generated high magnetic fields and capacitor banks. And so Los Alamos was chosen as the home of the PFF.

This time the project didn't fold, and over the past 28 years the generator has powered the PFF to new limits and world records. In 1997 the facility achieved the original goal of generating the first 60-tesla pulse to last longer than 100 milliseconds. And in 2012, facility scientists set a world record for the highest non-destructive magnetic field with their "100-tesla shot," a heart-stopping moment during which the facility's largest magnet surpassed 100 tesla for a thousandth of a second. That magnet, the crown jewel of the facility's user program, now routinely provides 95 tesla for scientists from around the world.

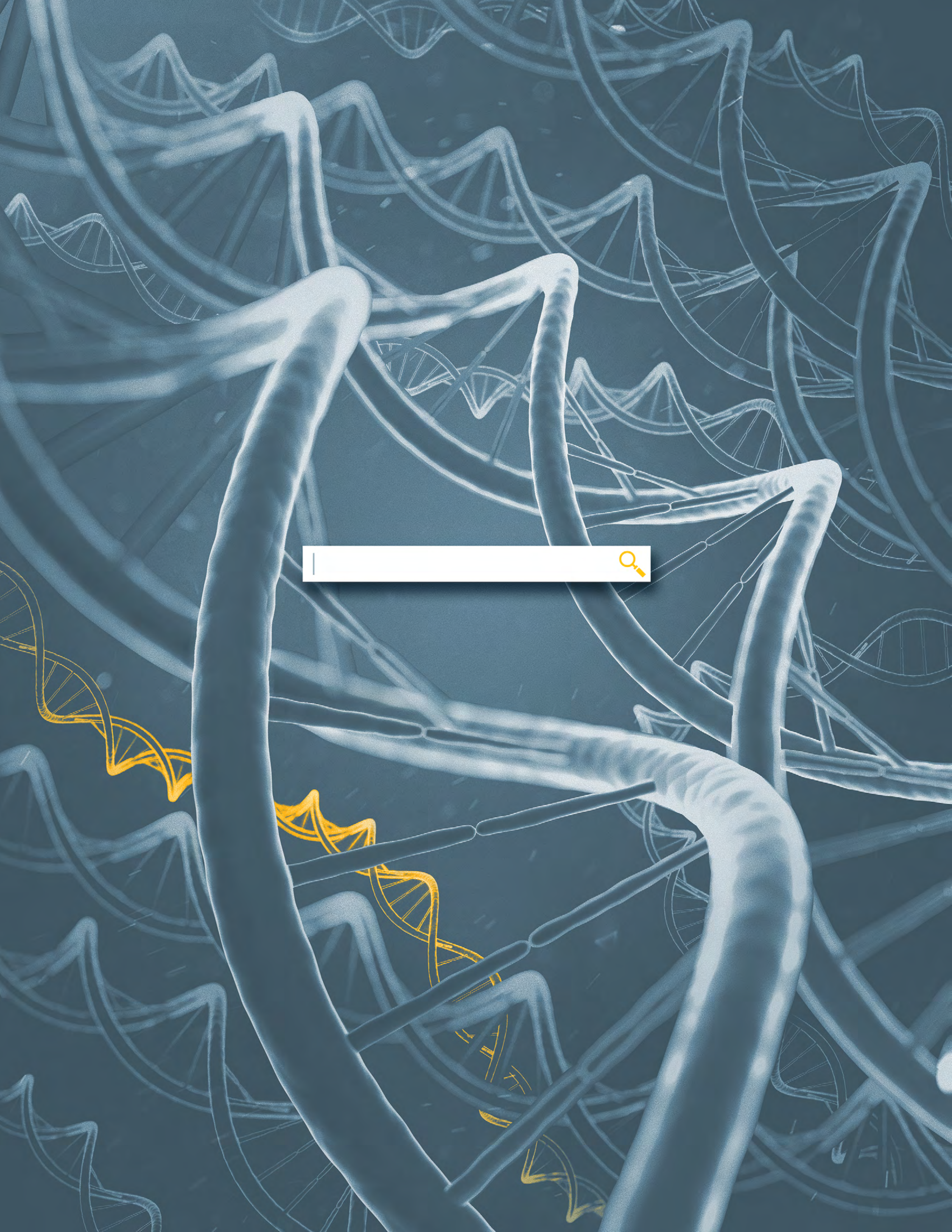
The machine behind the magnets alternates between motor and generator. First it's a motor, spooling up to store electrical energy from the grid. Then it's switched into generator mode and dumps this energy as a short but incredibly powerful burst—the generator itself is capable of a staggering 1.4 gigawatts—into the waiting electromagnets. All that power can raise a large magnet's temperature from −200°C to room temperature in a second or two. Between the heat from the current and the force from the magnetic field itself, these extreme electromagnets can only be used in quick pulses, lest they melt or blow themselves to bits.

The PFF boasts the most reproducible high-field magnets in the world. Scientists studying the physical properties of metals or superconductors, for example, need many pulses to really learn anything useful. A tiny sample of the material of interest is placed in the bore of the magnet, the magnet is turned on, measurements are made, the magnet is turned off, and the whole thing is reset to go again. On any given day, multiple teams of scientists from around the world may be running experiments; during the 100-tesla shot, experiments on eight different materials were performed simultaneously.

The PFF at Los Alamos embodies a coalescence of capabilities: very high magnetic fields, unique magnet designs and pulse shapes, exquisite temperature control, and innovative probes and measurement technologies. These capabilities, in concert, keep the facility at the forefront of the institutional, national, and global materials-research communities.

Sometimes it takes the very large—like a football-field-sized facility—to understand the very small—like the subatomic properties of semiconductors. And sometimes it takes three tries for a gigantic generator to find its fate.

—Eleanor Hutterer



Out of the approximately 69 trillion cells inside a human body, more than half of them are not human. They are microbial, belonging to thousands of distinct types of bacteria, archaea, and fungi. In addition to this are countless other types of bacteria, as well as viruses, found around our living environments—our houses, our pets, our backyards, and our communities. Clues about how we cohabitate with all these organisms are buried within each one's genetic material, or DNA. Although the vast majority of the microbes have not even been identified, much less studied, the few clues that have been deciphered foretell an enlightened future. From an understanding of the complex interactions between humans and the microbes that comprise these microbiomes may come the potential to revolutionize health and medicine.

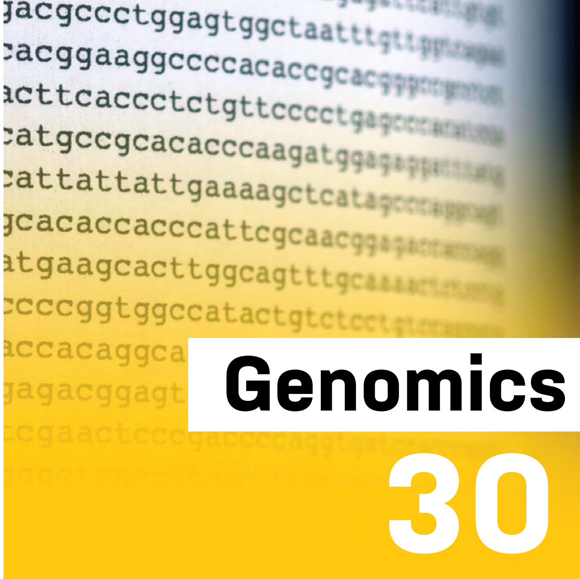
A genome is all of the genetic information from a given organism, including genes, non-coding sequences, and mitochondrial and chloroplast genetic material. Virtual mountains of genomic data are already available thanks to advances in DNA sequencing, and it is inevitable that the mountains are only going to get bigger.

Making Sense of SEQUENCES

Los Alamos **bioinformatics** is making it easy to interpret nature's hereditary code.

"Genomic data is being generated at a tremendous pace," says Los Alamos bioinformaticist Patrick Chain. "In fact, it has been said that by 2025 the amount of data produced each year will outpace Twitter, YouTube, and the entire science of astronomy combined." Chain explains that sometimes the data are used to uncover the reasons behind a disease like cancer, and sometimes they are used to trace ancestry. In other realms of biology, genomics is being used to better understand complex biological communities found in soils, lakes, oceans, or the human gut.

Bioinformatics is the interdisciplinary field that makes this analysis possible. Using DNA sequence data and bioinformatics, scientists develop knowledge about which organisms match which reference sequences; which other organisms they may be related to and in what way; how organisms function, thrive, and survive; and what relevance they have, directly or indirectly, for humankind. In order to begin answering these questions, scientists must compare unknown sequences with known ones (found in public databases, such as the primary U.S. repository named GenBank, founded at Los Alamos in 1982), and each question often requires a different approach or specialized software tool. However, regardless of the data availability, many clues remain hidden because rapid developments in sequencing technology, combined with the volume of data coming out of these machines, has created a data-analysis bottleneck. And the bottleneck is only getting tighter as the sequence data keep coming.



With this vast challenge in mind, Chain and his team at Los Alamos are making analysis easier, especially for scientists who are not bioinformatics experts. His team developed a user-friendly web interface called EDGE (Empowering the Development of Genomics Expertise) that combines openly available tools and databases to comprehensively answer any type of genomics question. And it's working: the award-winning EDGE platform has already been deployed to at least 14 countries and is helping scientists make sense of the sequences.

The genomics era

The availability of genomic data has revolutionized how living organisms are characterized, organized, and identified—no longer by their physical traits or lifestyles but instead by their internal blueprint of DNA or RNA. As such, these data are useful for many different areas of science and medicine. For instance, sequence data can help scientists verify relationships between species based on identifying genes in common, and doctors can—although the practice is not yet widely used—determine the exact strain of flu that is making a patient sick.

To make these kinds of determinations, the sequence data must be interpreted. Although there are a multitude of shared databases and open-source algorithms available, they generally require specialized expertise, so scientists wishing to use genomics to support their research typically choose to send data to external bioinformatics experts for analysis. This approach makes reproducibility difficult because each expert may use a different tool or protocol. It also increases cost and takes valuable time. Chain's team sought to change the paradigm by developing a way for nonexperts to use the algorithms themselves, without having to rely on external bioinformaticists' help. This required two important steps: identifying the right tools and developing a user-friendly way to access them.

GenBank contains over 3 trillion bases from genomes large and small.

"Having a suite of tools in the same place allows you to answer several questions at once and dig deeper into the data," says EDGE-team biologist Karen Davenport. "We're choosing the best quality open-source tools that are not too computationally intensive and putting them together to make working with them easier."

It's a little like tax preparation software: instead of wading through intimidating tax code and complicated forms, the software has an attractive interface with easy-to-understand questions, the calculations are done in the background, and the software spits out a dollar amount. With EDGE, the user looks at an attractive interface where she can set question parameters, the analysis is done in the background, and the software spits out an answer—sometimes as a data visualization.

"A graphic can quickly tell you something that would take a lot more time to understand by looking at a text file or data sheet," says Davenport.

EDGE also makes analysis faster: most tasks take minutes or hours, whereas outsourcing to specialists can take days or even weeks. In addition, EDGE is open source and it is possible to run the software on one CPU with only 16 gigabytes of memory (as on a high-end desktop computer). The development team is experimenting with cloud-based computing services as well.

The genetic code is represented by four letters, as shown here inside one of the books at the Wellcome Collection. More than 100,000 such pages are needed to express the entire human genome.
CREDIT: Wellcome Collection, Kerr/Noble

at Los Alamos is YEARS YOUNG

Three decades ago, Los Alamos scientists helped shape the future of biology by playing a foundational role in the Human Genome Project (HGP). This international project to determine the entire sequence of human DNA launched a new era of biology and medicine, but in 1986 when it was first proposed, not everyone was optimistic. In fact, many leading biologists told Congress they opposed the project, calling it "audacious" and "wasteful." Fortunately, the vision and leadership of a few key people, including Los Alamos's Scott Cram, Larry Deaven, and Robert Moyzis, and the late Walter Goad and George Bell, combined with the proven success of certain Lab capabilities in flow cytometry, gene library generation, and sequence database construction ultimately helped secure the $3 billion that forever expanded the reach of science.

Once the double-helix structure of DNA was resolved in the 1950s, scientists sought to determine the sequence of the chemical bases that pair together to create DNA: adenine (A), thymine (T), guanine (G), and cytosine (C), represented by a code of these four letters. The base pairs are arranged in a highly specific order that encodes all the hereditary information needed to create and maintain an organism. By the late 1970s, one could sequence about 20 base pairs in six months, and many of the sequences generated were being deposited in a publicly shared Los Alamos database called GenBank. However, as scientists began to envision sequencing the entire human genome—more than 3 billion base pairs—it became clear that doing so would require a leap in technology and strategy.

In the early 1980s, Los Alamos scientists made advances in two key areas that enabled this very leap: flow cytometry and the creation of gene libraries. Flow cytometry was invented by Los Alamos's Mack Fulwyler in the 1960s; it works by suspending cells in liquid droplets to sort and separate them based on various properties. In 1983, Los Alamos established a National Flow Cytometry and Sorting Research Resource, through which it made numerous advances to the technology. That same year, Lab scientists also began participating in the National Laboratory Gene Library Project (in collaboration with Lawrence Livermore National Laboratory) to make libraries of flow cytometry-sorted chromosomes for distribution worldwide to labs that were researching specific genes.

In 1986, Los Alamos scientists joined colleagues and Department of Energy (DOE) leaders at a workshop in Santa Fe, New Mexico, to discuss the possibility of sequencing the entire human genome. Although there was skepticism, the success of the Library Project demonstrated that flow-sorted chromosome libraries could be used to ensure enough copies of DNA would be available for sequencing such a large genome. In 1987, the DOE funded the HGP, and in 1990, the National Institutes of Health (NIH) and many international partners joined the initiative. Each partner was assigned certain chromosomes to sequence, and throughout the project, Los Alamos and Livermore provided the critical DNA libraries. Los Alamos also took on the job of sequencing two of the 23 chromosomes: 5 and 16. In (retroactive) recognition of the value of the Lab's seminal role in the HGP, Cram, Deaven, and Moyzis were awarded the Los Alamos Medal, the Lab's highest honor, earlier this year.

The results of the HGP gave scientists a better understanding of genetic diseases, including cancer, but that's not all; it also demonstrated the value of studying an entire genome. For instance, by studying the genome (instead of only particular genes) scientists have discovered that large sections previously called "junk DNA" actually encode important regulatory functions. Furthermore, the HGP showed the benefits of highly collaborative research and launched a revolution in technology that drastically reduced the cost of sequencing. With this, scientists began to sequence everything—DNA from the soil surrounding a tree root, the lining of the human gut, the handrails of the New York City subway—and it has revealed a whole new view of the world around us: one in which microorganisms vastly outnumber humans, animals, and plants. According to the NIH, the number of bases entered into GenBank from 1982 until now has doubled approximately every 18 months.

But the sequences alone do not create understanding. Quality bioinformatics is the bridge between big data and useful scientific knowledge, and this requires yet another strategic leap. That's where EDGE comes in.

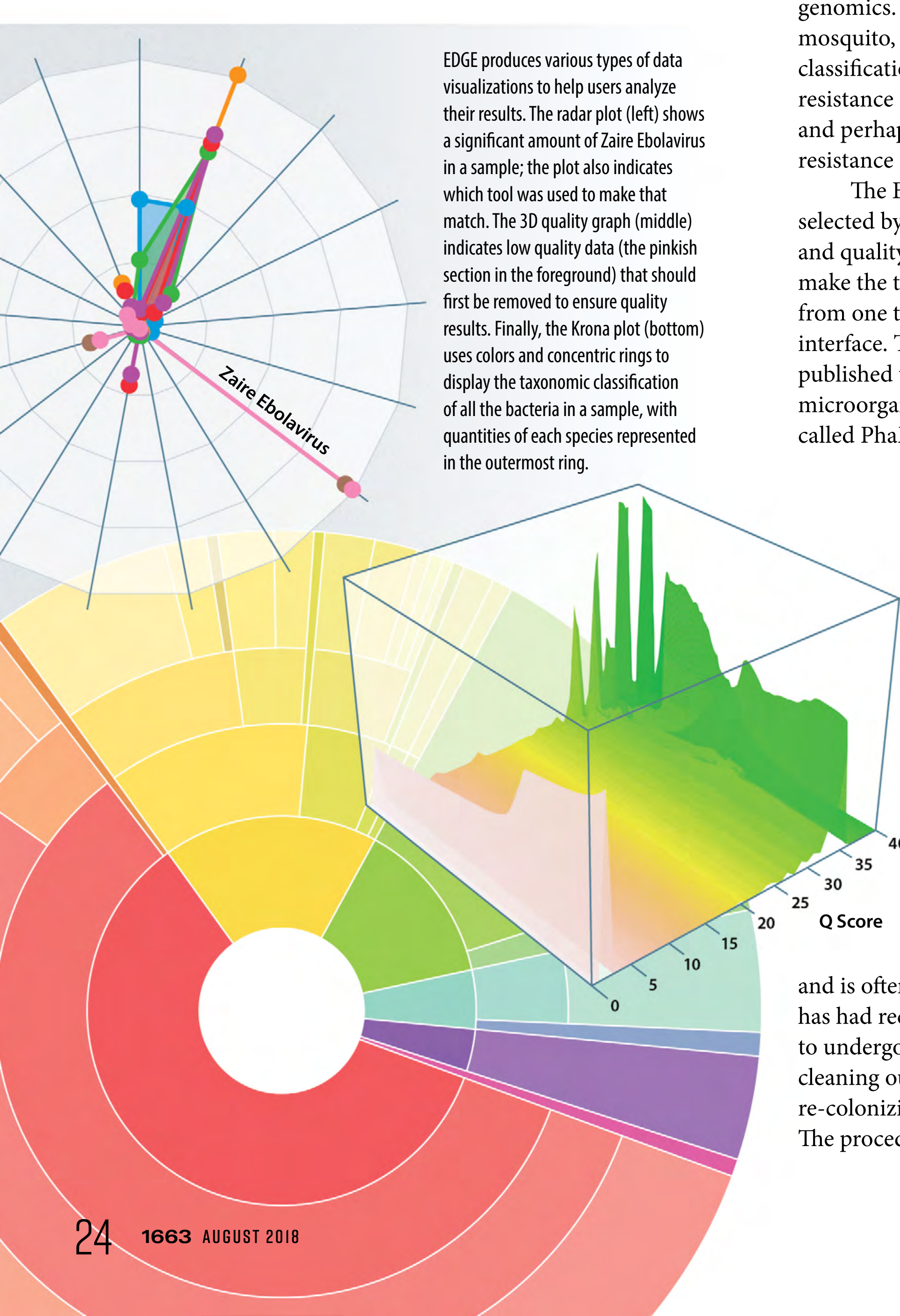
The Human Genome printed: 109 books, 1000 pages each, 3 billion letters.

The Wellcome Collection in London is home to the printed volumes of the data from the Human Genome Project. Organized as one volume for each of the 23 chromosomes, the entire collection contains 109 books, each with 1000 pages of tiny letters—ATGC.
CREDIT: Wellcome Collection, Gitta Gschwendtner

EDGE 101

When an organism's genome is sequenced, it is cut up into tiny pieces called "reads" that vary in length, depending on the type of sequencing machine that will be used. The machine then determines the order of the nucleic acid bases—adenine (A), thymine (T), guanine (G), and cytosine (C)—for each of the reads. Traditionally, the first role of bioinformatics is to put the pieces back together into larger contiguous sections (called contigs), which can eventually be used to reconstruct a gene (about 1000 base pairs) and then an entire genome; this is called assembly. Interpreting what the genes "say" is the next step, which involves a lot of matching against gene sequences from previously studied organisms in various databases.

Some samples of interest today, such as human-derived microbiome samples, contain more than one organism's genome—these samples are called metagenomic. For instance, a clinical sample could contain human cells, microorganisms from the person's microbiome, and hopefully some of whatever pathogen is making the person sick. Such diverse samples make for extremely complicated analyses because, with the exception of RNA viruses, all the reads are comprised of different arrangements of the same ATGC letters no matter what organism they came from. Therefore it may be undesirable to do assembly first because of the number of different genomes; instead, the strategy would be to simply compare reads to various reference genomes.



EDGE produces various types of data visualizations to help users analyze their results. The radar plot (left) shows a significant amount of Zaire Ebolavirus in a sample; the plot also indicates which tool was used to make that match. The 3D quality graph (middle) indicates low quality data (the pinkish section in the foreground) that should first be removed to ensure quality results. Finally, the Krona plot (bottom) uses colors and concentric rings to display the taxonomic classification of all the bacteria in a sample, with quantities of each species represented in the outermost ring.

"No algorithm is perfect," says Chain. "And different perspectives can show you different things about the data." With this in mind, EDGE was designed to have multiple options and workflows. The EDGE software uses different algorithms to answer different questions, based on the workflows chosen by users. A user might want to match genes with their function, a process called annotation, or instead the user might simply want to identify if a specific gene of interest is present.

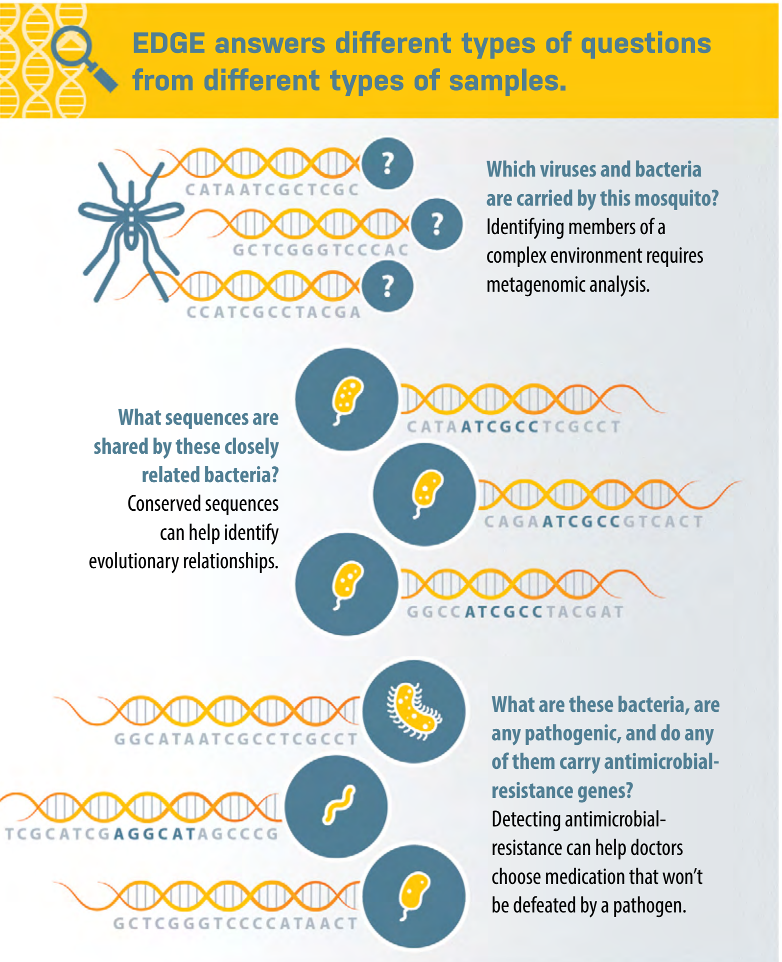
"To determine the relatedness of a known anthrax or plague culture, we might do assembly and comparative genomics. Or to identify everything that is present in a mosquito, we would do read- or contig-based metagenomic classification," says Chain. "Or if we are looking for antibiotic resistance genes we would examine assembly annotations and perhaps search reads as well, using a tailored search for resistance genes."

The EDGE platform contains over 100 published tools selected by criteria pertaining to their computational intensity and quality. The EDGE team wrote custom algorithms to make the tools work together—sometimes using the output from one tool as the input for another—and with the user interface. The team also included some of its own previously published tools, such as a database of unique signatures for microorganisms called GOTTCHA and a phylogeny module called PhaME.

On the EDGE of a breakthrough

Los Alamos postdoc Anand Kumar was trained as a veterinarian and an experimental microbiologist, so he does not have a lot of experience with writing algorithms. His current research project is to examine the disease-fighting members of the human gut microbiome. He needs to know which organisms he is dealing with and what genes they have—and the EDGE platform is helping him get results.

Specifically, Kumar wants to find out which organisms and byproducts naturally kill the bacteria *Clostridiodes difficile*, or *C. diff*, so that they can be used to treat *C. diff* infections. *C. diff* causes debilitating diarrhea and is often resistant to antibiotic treatment. When a patient has had recurring *C. diff* infections, he or she is often advised to undergo a fecal transplant, which involves completely cleaning out the microbiome of their intestinal tract and then re-colonizing it with a slurry of microbes from donor feces. The procedure is very effective because the microbiome of



Scientists are studying the human microbiome to learn which symbiotic relationships make us healthy.

a healthy individual contains millions of beneficial bacteria, some of which secrete chemicals that can actually kill dangerous bacteria. (These types of chemicals are the origins of many current antibiotics, although there are still hundreds of unknown species and potential drugs yet to be identified.) The downside to fecal transplants, however, is they are not widely available due to FDA regulations and not without side effects and the risk of other diseases.

Using an experimental technique developed at Los Alamos, Kumar is in the process of isolating microorganisms found in successful fecal transplant samples to look for ones that show a propensity to kill *C. diff* bacteria. Once isolated, he can sequence them and use EDGE to analyze what he's found—are they new species? How do they fight against *C. diff* bacteria? Do they have genes that are associated with potential antimicrobial activity?

Kumar's goal is to use what he learns about these *C. diff*-killing microbes to create probiotic pills that people can take instead of having a fecal transplant. By including only the most effective organisms—instead of recreating the entire fecal sample in a pill—Kumar says the risks of side effects will be lower, and patients should have a better experience. Furthermore, he favors the probiotic approach over simply siphoning off the antimicrobial chemicals to be used as drugs for treatment. He explains that, although many commercially available probiotics do not tend to remain in adults' intestines for long, the beneficial bacteria in his study originate in a healthy adult and could be different; they could colonize the new patient's intestine permanently, leading to long-term protection.

Although EDGE is already streamlining research for scientists worldwide, one place where EDGE has the potential to make an enormous change is in the public-health sector. Antibiotics are often prescribed unnecessarily because doctors don't have an easy and affordable way to determine exactly which bacterium or virus is making a patient sick. This misuse of antibiotics is leading to a rise in antibiotic and antimicrobial resistance.

EDGE provides tools that could help with this issue. As more medical clinics choose to purchase sequencing technology—which is already beginning and is likely to be widespread in the next few years—EDGE would make it possible for doctors and technicians to identify what pathogen is causing an illness. Furthermore, EDGE can also help determine if the culprit is resistant to certain drugs, and if so, which alternative drugs will be most effective.

Thirty years ago, the Human Genome Project prompted a revolution in sequencing technology that enabled the widespread proliferation of genomic data. It is through this flood of data that scientists have begun to fully appreciate the value of microbiomes and the symbiotic relationships humans have with microorganisms. Although the complexity of this new world view leaves scientists with more questions than answers, enlightenment is on the horizon. While some use genomics to understand what is making people sick, others are studying the microbiome to learn what symbiotic relationships make us healthy. And bioinformatics is key to making it all make sense. LDRD

—Rebecca McDonald

More **genomics** at Los Alamos

http://www.lanl.gov/discover/publications/1663/archive.php

- **Metagenomics and nutrient cycling in soils**
  "In Their Own Words" March 2018
- **Genomic clues to cancer's origin**
  "What Causes Cancer?" December 2016
- **New reference genomes aid metagenomic analysis**
  "Microbiome References Required" August 2014
- **DNA sequencing after the Human Genome Project**
  "Unraveling Life Four Letters at a Time" November 2013

SNAPSHOTS 75 SEISMIC EVENT MONITORING FROM THE HILL

READING RUMBLINGS IN THE EARTH

Nuclear weapons have existed for 73 years. And for 73 years, scientists have been monitoring nuclear detonations from afar by the vibrations they send through the ground beneath our feet. But nuclear explosions aren't the only events that produce tremors in the earth; earthquakes, volcanic eruptions, mining operations, and chemical explosions all produce seismic signals. In keeping with the Laboratory's national security mission, when something sizeable makes the ground shake, Los Alamos scientists need to be able to say, with certainty, what it was.

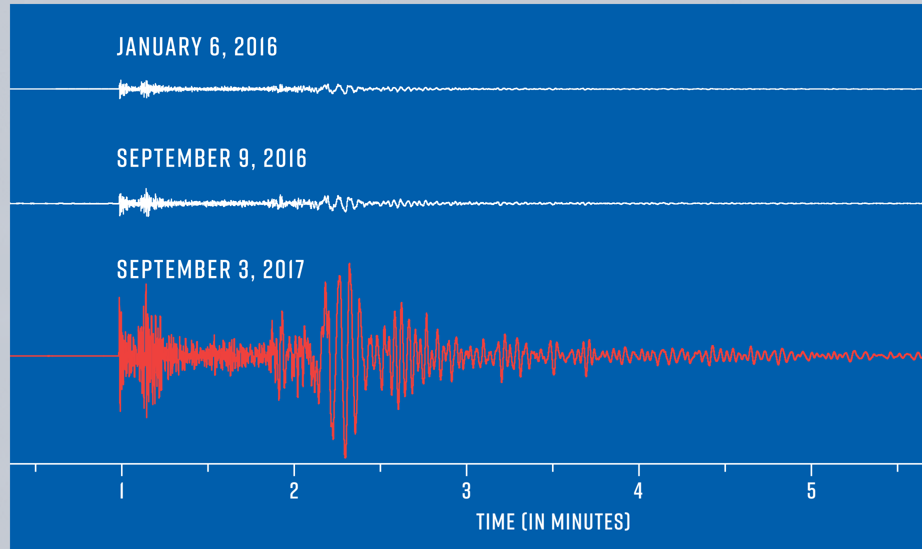
The first nuclear detonation—the Trinity test—took place at 5:29 a.m. on Monday, July 16, 1945, near Alamogordo, New Mexico. Numerous seismometers (some incidental, having been permanently deployed by universities, observatories, or other agencies, and some temporary, having been set out specifically for the test) were located at various distances from ground zero. Most of the temporary devices registered virtually no activity, but at least three of the permanent devices did pick up something. At a U.S. Coast and Geodetic Survey station in Tucson, Arizona, 270 miles away from Alamogordo, at approximately 5:30 that morning, a seismometer needle suddenly began to move, swinging rapidly up and down across the slowly rolling paper for about three minutes. The survey-station scientists didn't know it at the time, but they had just seismically detected, for the first time, a nuclear detonation.

For the first two decades of the nuclear age, as different countries developed their own weapons, tests were usually conducted above ground, so monitoring technology focused on signatures in the air. In 1963, the Limited Test Ban Treaty forced nuclear testing to move underground and, as a result, seismology became a national security research priority. Throughout the Cold War years, seismology was used to help discriminate explosions—both chemical and nuclear—from earthquakes whenever and wherever they occurred in the world.

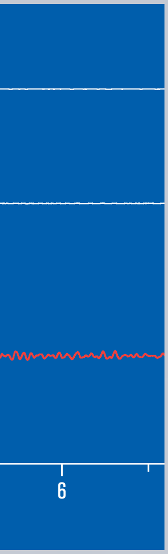
More recently, however, smaller-magnitude events have made the challenge of detection and characterization more complex. The information about these smaller, suspect events is embedded in a noisy background of nuisance events, occurrences in our busy world that produce seismic signals. So as the real signals are getting smaller, the background noise is not, and distinguishing between the two presents a formidable technical challenge.

During the Cold War, ground-based nuclear-detonation detection was comparable to studying an aerial image and asking, "Is there a city there or not?" Now, because scientists are looking for finely detailed signals in an overwhelmingly noisy background, the analogous query would be, "Is there a vehicle parked on a particular corner, and if so, is it a car or a truck?"

Seismically, small explosions look more like earthquakes than large explosions do. To distinguish between explosions and earthquakes, scientists need to understand the effects that surface topography, local geology, and subsurface structure have on



Modern seismograms are computer generated, allowing for finer and more detailed analysis. These three traces were produced by a detector located in China and record the most recent announced nuclear-weapons tests conducted in the Democratic People's Republic of Korea (North Korea), which publicly claimed that the last one was a thermonuclear weapon, also known as a hydrogen bomb.



the signals they receive. There are regional differences in the way seismic signals propagate through the subsurface, depending on the unique geology of each region. In the 1990s, Los Alamos, in coordination with several other national labs and federal entities, began the Ground-based Nuclear Detonation Detection program. The goal was to leverage decades' worth of underground nuclear test data to create new systems for monitoring and characterizing potential nuclear explosions around the world.

Gone are the days of pen-to-paper seismographs—modern seismology is conducted with computers. And seismology at Los Alamos is conducted with supercomputers. Large computational experiments help scientists understand how seismic waves propagate from a single source through the earth and into the atmosphere. This understanding, in turn, helps scientists discern different types of man-made explosions as well as natural disturbances.

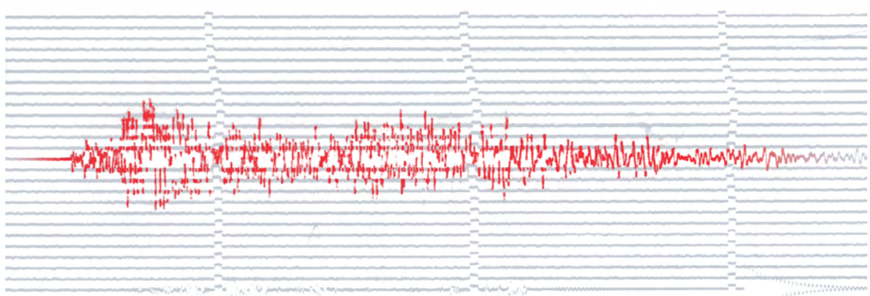
As the Laboratory develops machine-learning techniques to help meet challenges across many fields, the Ground-based Nuclear Detonation Detection program is leveraging these capabilities to help solve the signal-to-noise discrimination problem. The program is building a reliable, predictive computer-modeling framework that uses multiple signatures. Rather than relying on a single signature, this approach to explosion monitoring combines ground-based seismic and acoustic data with chemical, satellite, and ocean data into a comprehensive explosion monitoring system.

With a combination of supercomputer simulations, newly developed analytical techniques, and expanded data sets available for monitoring activity across the globe, the new system will build on the Laboratory's confidence in its detonation-detection and evaluation abilities.

The national labs take on the hardest scientific problems, and the toughest technical tasks, all in support of the nation's security. At its inception, the Laboratory was tasked with building the bomb, and the capabilities that have evolved from that first charge continue to serve the Laboratory's mission, 75 years later. Los Alamos achieves the tasks of monitoring nuclear programs, ensuring treaty adherence, and continuing stockpile stewardship through the most rigorous and robust scientific capabilities.

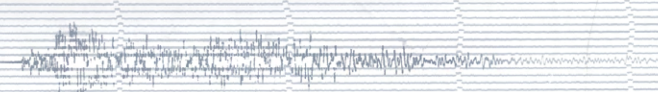
So when something makes the ground shake, somewhere in the world, scientists here at Los Alamos are primed and ready to determine what, where, and how big it was.

—Eleanor Hutterer



The first-ever nuclear-weapon test, the Trinity test, is recorded on this seismogram, from July 15 and 16, 1945, from a seismometer located in Tucson, Arizona, as part of the U.S. Coast and Geodetic Survey. At approximately 5:30 a.m. on the 16th, a seismic disturbance lasting about three minutes was recorded, which, though not known at the time by survey scientists, was caused by Trinity, 270 miles away.

CREDIT: This image was scanned from a microfilm that was produced in the course of the Historical Seismogram Filming Project of the 1980s (http://ds.iris.edu/seismo-archives/info/publications/Lee1988.pdf). The U.S. Geological Survey in Denver, Colorado, holds both the microfilm and the original document. Digital scan courtesy of Jim Dewey/USGS.



Whether a seismic disturbance came from an earthquake, an industrial accident, or a nuclear weapon, scientists need to know.

AN ENDURING LEGACY FOR THE NEXT 75 YEARS

1663 asked Laboratory Director **Terry Wallace** how the Lab's illustrious history positions it for the scientific discoveries that will be needed in the future.

IN THE SPRING OF 1943, J. ROBERT OPPENHEIMER began to assemble his scientific team on the isolated mesas of the Pajarito Plateau in Northern New Mexico. This team comprised some of the brightest scientists from across the nation, as well as several refugee scientists from Europe. Most had only a modest inkling at best of the nature of the project they were going to be working on, so the first stop on this great scientific rendezvous was a series of lectures organized by an Oppenheimer protégé, Robert Serber. Serber had been working with Oppenheimer on a framework for nuclear-fission weapons for about a year and had remarkable skill in bridging theoretical and experimental views in nuclear physics. His lectures were attended by giants in the field, including Enrico Fermi, Hans Bethe, Edward Teller, and Stanislaw Ulam, along with scores of younger staff, many with newly minted PhDs. Serber introduced the lectures with a simple summary of why everyone had been called to Los Alamos: "The object of the project is to produce a practical military weapon in the form of a bomb in which the energy is released by a fast-neutron chain reaction in one or more of the materials known to show nuclear fission."

These lectures were legendary, and each lesson generated debate and new insights. Out of these lectures, the science plan for Los Alamos emerged. Scientists and engineers were based in disciplinary groups (theory, physics, chemistry, metallurgy, ordnance, etc.), and work began on hundreds of aspects of the problem. The pace of discovery was extraordinary. By the end of 1943, Bethe and Richard Feynman had developed a fundamental formula for the efficiency of nuclear chain reactions that could be used to calculate the yield of fission bombs, the first phase diagrams of the newly discovered element plutonium were determined (but remained to be fully explained for decades), and precisely timed exploding-bridgewire detonators were invented. As a measure of this scientific creativity, Los Alamos filed several thousand patents for various parts spanning an enormous scope. (The patents were filed in secret in order to hide the scientific path to an atomic bomb.)

The 75-year history of Los Alamos is rich with discovery. The science plan today is driven by the same principles as Oppenheimer's original plan: Define the hard problems that need to be solved and realize that the solutions must draw from a broad spectrum of disciplines. Los Alamos discoveries and technological advances have changed the way we live and how we understand the universe. Nuclear energy, nuclear medicine, the discovery of gamma-ray bursts, the invention of the heat pipe (which makes all smartphones possible), decoding the human genome, supercomputing, finding evidence of ancient lakes on Mars—all these breakthroughs are because of our interdisciplinary history.

The challenges in the coming decades—the next 75 years and beyond—are as formidable as those faced by the scientists and engineers that gathered on the Pajarito Plateau in 1943. Every year, the directors of the nation's nuclear-weapons laboratories are asked to assess the safety, security, and effectiveness of our nation's nuclear stockpile and report back to the Secretary of Energy and, ultimately, the President of the United States. Since the country's last nuclear test in 1992, we have used our expertise in science and engineering to do just that. The nuclear arsenal is the cornerstone of our country's strategic deterrent, and maintaining its credibility is the thrust of the Laboratory's work. From that work stems other critical missions—including supporting nuclear nonproliferation and counterproliferation. Our expertise in all things nuclear gives us the ability to develop tools to monitor the globe for nefarious nuclear activity, train international nuclear-facility inspectors, disable an improvised nuclear device, and conduct forensics on nuclear materials to determine their origin. We also use science to tackle emerging threats—whether they be biological, cyber, chemical, or climate. At every turn, we look at the biggest challenges to our national security and work to find scientific and engineering solutions.

None of this work is easy, but it is essential—and that is why we approach it with both rigor and respect—just as the men and women of the Manhattan Project did. It is an enduring legacy that will continue to guide us far into the future.

CREDIT: Michael Pierce/LANL

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This postcard was made by the Tichnor Brothers of Boston, Massachusetts, between 1930 and 1945—during which time the Laboratory at Los Alamos was established. Parades in modern-day Santa Fe still travel along Palace Avenue, named for the building seen here, the Palace of the Governors. Newly arriving scientists were received at 109 East Palace Avenue, the building at the right edge of this picture. This office was also the delivery location for mail addressed to P.O. Box 1663, Santa Fe, NM—the single address that served all the residents of The Hill, about 35 miles northwest of Santa Fe. *CREDIT: Boston Public Library*

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